Department of Applied Geology

Impacts of Mining and Mine Closure on Water Quality and the Nature of the Shallow Aquifer, Yandi Iron Ore Mine.

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ABSTRACT

The Hamersley Yandi Iron Ore Mine of Hamersley Iron Pty. Ltd. is located in the Pilbara region, Western Australia, approximately 90km north west of the town of Newman. The iron ore has accumulated in a palaeochannel as an enriched Channel Iron Deposit (CID). Mining in other parts of this palaeochannel has been practised since 1991. Named deposits in the province are, from west to east, Munjina, Pool, Meander, Western, Central, Eastern, Junction and the Billiard deposits.

Presently the CID acts as an aquifer and transmits water through its fracture system. It is the main conduit for the regional groundwater. The Water and Rivers Commission of Western Australia considers the groundwater in the alluvial beds of the Weeli Wolli Creek overlying the CID to be a useful resource. The groundwater is currently used for stock watering so the quality should be preserved.

Part of the four possible closure plans of the Yandi Mine is to backfill the excavated channel with waste rock from the mining operation. The waste material will consist of the uneconomic grade lateritic pisolite iron ore, together with colluvium and alluvium overburden. The closure plans will also leave behind two pit lakes.

The impact of these closure plans vary but each plan will leave pit lakes containing water with high salinity and this may adversely affect the quality of the groundwater downstream of the lakes.

The hydraulic conductivity of the shallow aquifer may be impaired by swelling clays found in parts of the waste material. This impact would be reduced if the chosen closure plan was one with hydrogeological flow management.

The water quality downstream of the pit lakes will change and the environmental impact on the groundwater will depend on which closure plan is chosen. This thesis suggests a number of options for consideration.

ACKNOWLEDGEMENTS

This thesis could not have been completed without the following people:

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INTRODUCTION

1.1 BACKGROUND OF STUDY

The Yandi Iron Ore Mine[1] of Hamersley Iron Pty. Ltd. (Hamersley Iron) is located in the Pilbara region, Western Australia, approximately 90 km north west of the town of Newman (23° 21.7S, 119° 44.8E). The location of the mine is shown in Figures 1.1 and 1.2. The iron ore formed as an enriched Channel Iron Deposit (CID) in the ancient river channel (palaeochannel) of the Marillana Creek.

The Marillana CID is the main conduit for regional groundwater transportation to the Weeli Wolli Creek system. Fractures in the CID allow relatively easy passage of groundwater along the palaeochannel. The Water and Rivers Commission of Western Australia considers the groundwater in the alluvial beds of the Weeli Wolli Creek and in the underlying CID to be a potentially useful resource. The groundwater is currently used for stock watering, so the quality should be preserved.

1.2 AIMS OF STUDY

This research project has the following objectives:

- To determine the current water quality in the aquifers.
- To predict future water quality after waste rock from the mining has been returned to the channel.
- To predict the physical properties of the groundwater system after the waste has been returned to the channel, and particularly to assess any changes in permeability occurring as a result of siltation or secondary mineral formation.

[1] The location is also known as Yandi Junction and Yandi Loop. These names are derived from the position of the mine on the meander or loop where the Marillana Creek joins the Yandicoogina Creek.

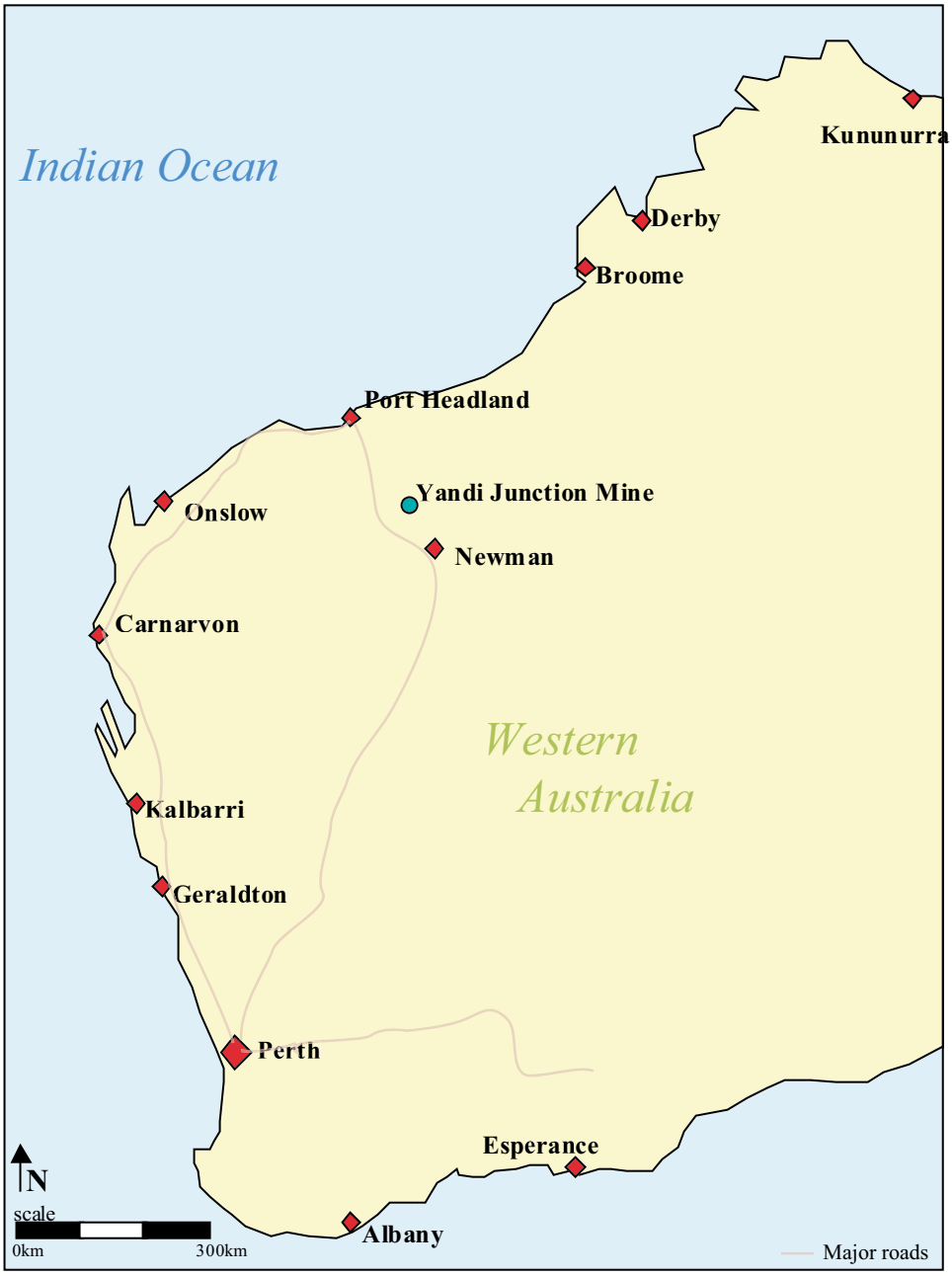


Figure 1.1

LOCATION OF THE YANDI JUNCTION MINE SITE

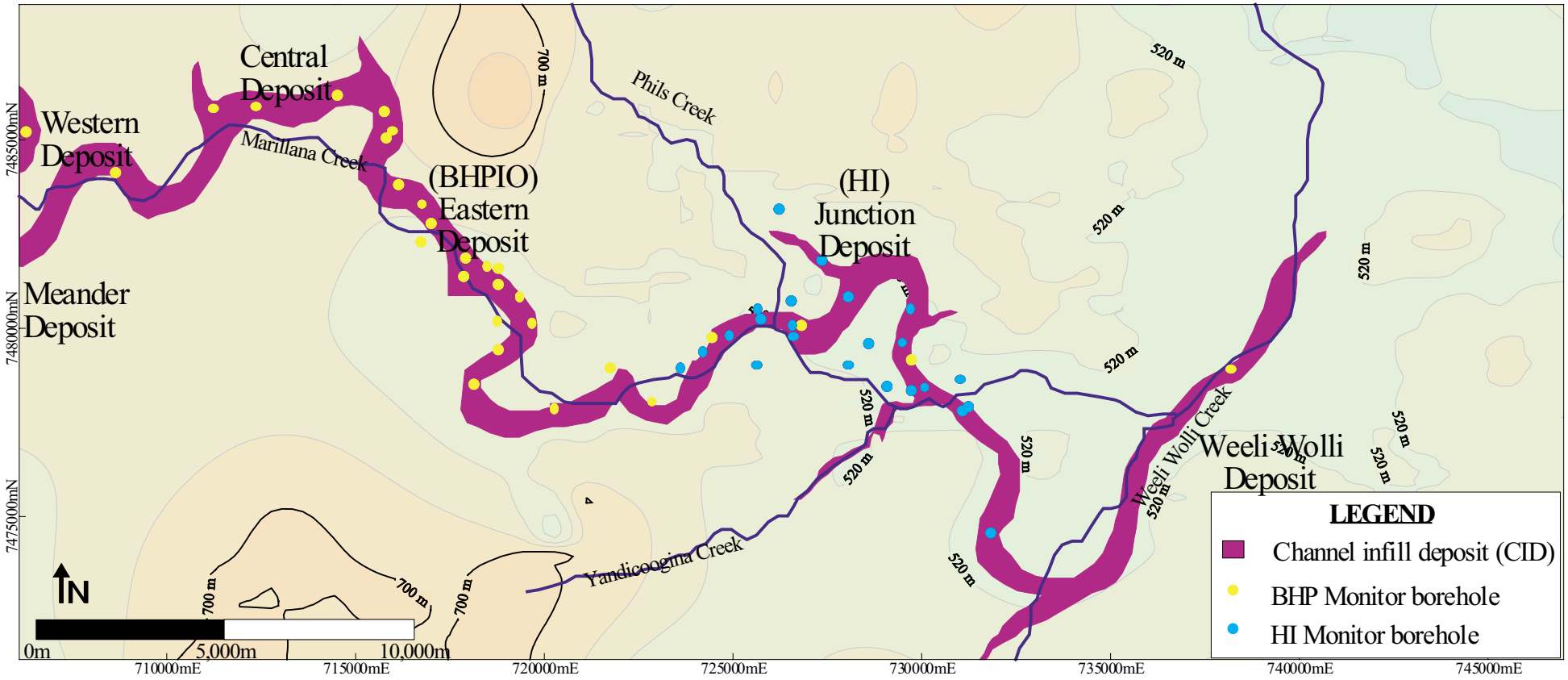


Figure1.2

MONITOR BOREHOLES LOCATIONS ALONG THE CID

BHPIO - BHP Iron Ore mine
HI - Hamersly Iron mine
Horizontal Datum: AGD66
Zone 50 Australian map grid

1.3 HISTORY OF INVESTIGATIONS

Hamersley Iron, Broken Hill Proprietary Co. Ltd (BHP), now BHP Billiton and CSR Civil Contracting (CSR) have all investigated the iron ore deposit at Yandicoogina.

The ore body was discovered in 1963 by BHP. CSR discovered additional ore deposits proximal to the BHP deposit and acquired tenements for these deposits in 1969 (Hamersley Iron Pty Ltd 1995). These deposits have been studied extensively, including mining and metallurgical mapping, drilling, geophysical surveys and feasibility studies. In 1987, Yandcra Ltd purchased the Yandi Junction deposit from CSR. Hamersley Iron and Yandcra Ltd were both subsidiaries of Conzinc Rio Tinto of Australia (CRA) now Rio Tinto Ltd. Geological studies of the Junction deposit were undertaken by CRA. These studies showed an increase in iron ore grade downstream and a combined ore reserve of 1900 Mt (1100 Mt CSR and 800 Mt BHP).

BHP completed investigations of the same CID 5 km and 11 km west of the Hamersley Iron Yandi Junction mine for the BHP Yandi C1/C2 (Central deposit) and Yandi E2 (Eastern deposit), respectively. The investigation included explorative drilling to establish the extent and grade of the deposit. The Eastern deposit E2 mine became operational in 1992. A Consultative Environmental Review (CER) by AGC Woodward-Clyde Pty Ltd was commissioned in 1995.

CSR conducted diamond drilling at the Snooker, Meander and Junction deposits to identify Initial Mining Areas (IMA). The drilling program was conducted during 1993, together with a number of trial studies as part of research and development. Geostatistical studies were also completed. Diamond drilling was found to be the drilling method with the least bias, and increased the estimated reserve to 4,700 Mt (2,900 CSR and 1,800 Mt BHP).

Test work on cores from the 1993 diamond-drilling program was completed in 1994. Further research and development was completed by ATD to determine whether silica could be removed. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Mineral Industries Research Association (AMIRA) completed a report on the CID, that showed the deposits to contain high iron and low aluminium, silica, sulphur and phosphorus.

In 1995 further drilling was commenced in the IMA at Yandi Junction. Research and development continued with a restripping test pit, crushing and screening trials and a wide core drilling program. Development of a detailed mining plan was completed in 1996.

Hamersley Iron bought the exploration rights for the Yandi Junction mine from CSR in 1997. Further exploration drilling and a CER of the mining project (Hamersley Iron Pty Ltd, 1995) was completed. The Hamersley Iron mine became operational in 1998.

Hydrogeological investigations on the affects of pit closure by A. J. Peck and P. M. Clifton are continuing.

1.4 CLIMATE

The Pilbara region experiences a semi arid climate, with most rainfall occurring during the summer months. Total annual rainfall is variable due to the unpredictable nature of prevailing cyclonic events and thunderstorms. Much of the rain falls during cyclonic events, when flooding frequently occurs along creeks and rivers. The major water courses in the region are highly ephemeral. Annual rainfall at stations close to the Yandicoogina mine ranges from 0.18 m to 0.35 m.

The winter climate is dry and the temperatures are mild with occasional frosts at night (Youngman, 1997). Evaporation in the Pilbara region is between 2 m and 3.5 m, ten times greater than the rainfall (Stoddart, 1997). The few surface water bodies that survive during the dry season are hypersaline due to the rapid evaporation rate and variability of flow.

Records have been kept only for the last 40 years and may not accurately reflect the inconsistent rainfall in the Pilbara. A year's rainfall for the Yandi Junction mine can occur in one day. Tropical cyclone 'Steve' in March 2000 contributed 0.20 m to 0.30 m of rain to areas in the Pilbara (Fisheries Western Australia, http://www.wa.gov.au/westfish/comm/broc/mp/mp127/fmp12707.html 1999).

Figure 1.3 shows the total rainfall and the mean maximum temperature for Western Australia from 1st May 1998 to 30th April 1999. The distributions show the Pilbara region to have a warm climate with a high total rainfall.

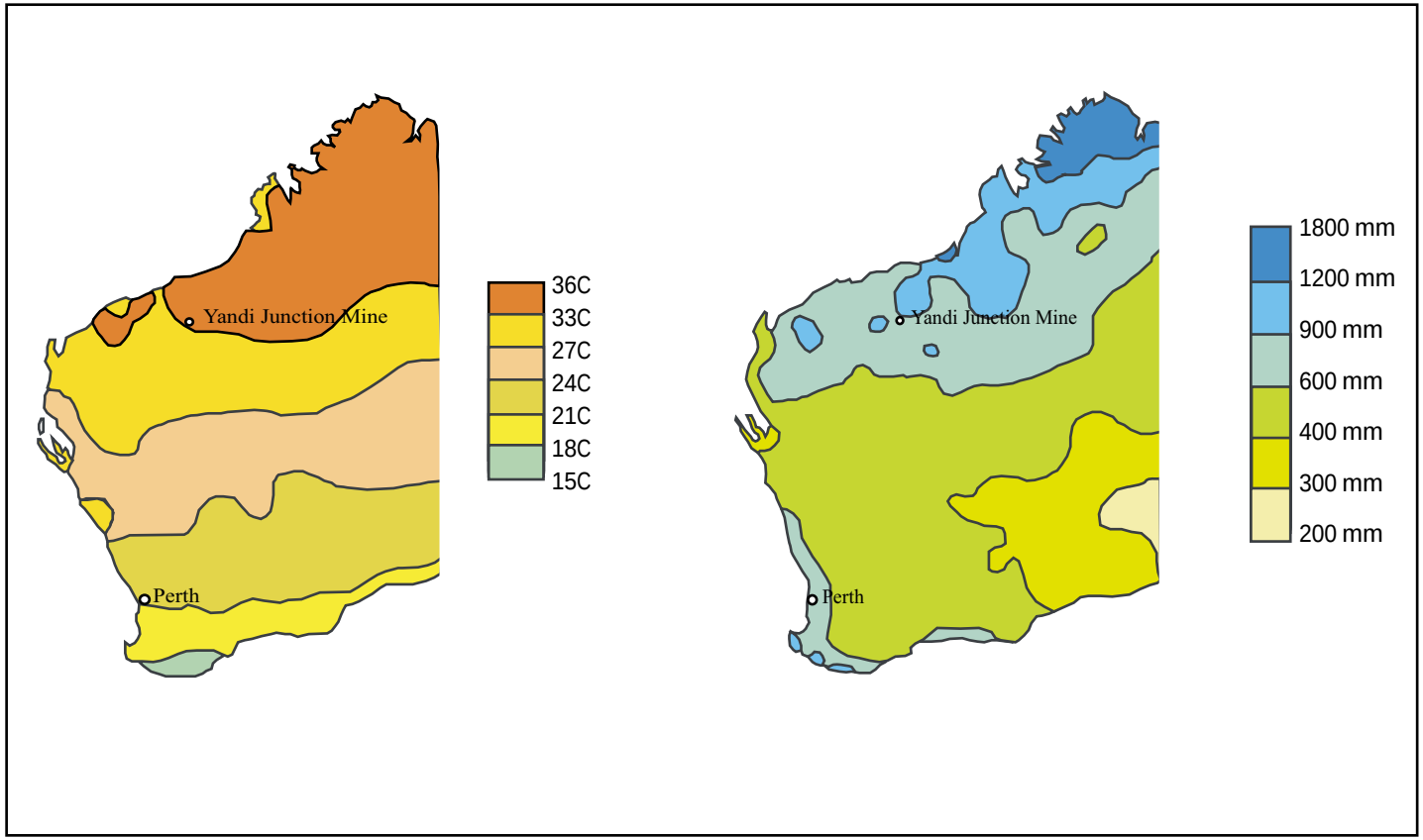


Figure 1.3

CLIMATE OF WESTERN AUSTRALIA (http://www.bom.gov.au/climate/)

1.5 GEOLOGY OF THE IRON ORE DEPOSIT

The geology of the Yandi Junction iron ore deposit has been reported by Youngman (1997, 1998) and Hall and Kneeshaw (1990), the former providing a 1:10,000 geological map. These geological studies form the basis of the following summary.

The lithologies have been divided into four groups:

- Proterozoic and Archaean basement rocks.
- Proterozoic to Quaternary altered basement rocks.
- Early Tertiary Channel Iron Deposit.
- Tertiary and Quaternary overburden material (subject of this investigation).

The stratigraphy of the area is summarised in Table 1.1.

1.5.1 BASEMENT ROCKS

The basement rocks are of Archaean and Proterozoic age and consist of Banded Iron Formation (BIF), shale, dolerite and dolomite. The scarp of the Hamersley Ranges to the north of the minesite is composed of these basement rocks. Jointing and folding is present from six deformation events (Youngman, 1997). The most significant structural feature is the Yandicoogina Syncline, which controls the geomorphology and ultimately the location of the CID and present drainage system. A further major feature that influences the landscape is the upland that developed about 135 Ma ago.

Wittenoom Dolomite

This formation is not present near the Yandi Junction deposit but is found upstream. It is predominantly dolomitic, and probably contributed significant proportions of calcium, magnesium and alkalinity to the present and past groundwater systems. Erosion of the carbonate-rich Wittenoom Dolomite is one of the mechanisms thought to be responsible for formation of the Oakover calcrete during the Pliocene and Miocene (Youngman, 1997).

Brockman Iron Formation

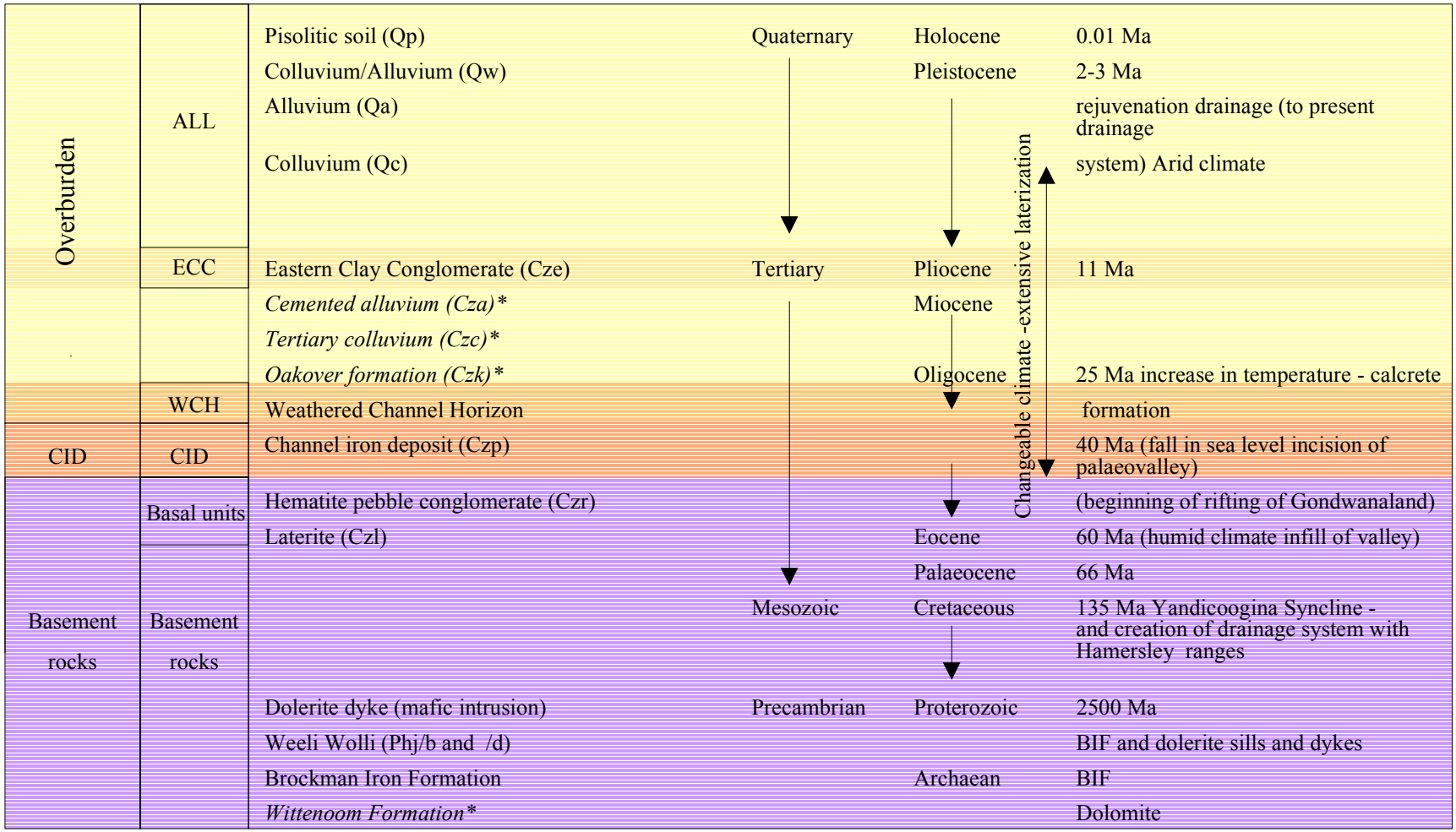
The early-Proterozoic Brockman Iron Formation is a banded iron formation. It was the source of the ferric detritus that had oxidised, hydrated and leached to form the CID. The formation includes the following members: Dales Gorge, Whaleback Shale, Joffre and the Yandicoogina Shale.

Weeli Wolli Formation (Phj/b)

The Weeli Wolli Formation is a BIF sequence of units of early-Proterozoic age separated by shale and siltstone bands. The formation has no perceived economic significance for the mining project.

Dolerite sills cut through the basement rocks. Variations in grain size and colour suggest that the sills were a result of multiple magma injections (Youngman, 1997).

Table 1.1 **Stratigraphy of the study area**



*Note * and italic are not found as channel fill, but are near the Yandi Junction Deposit*

Modified after Hamersley Iron (1996)

An east-northeast trending, coarse-grained dolerite dyke cuts through basement rocks north of the Junction deposit. The dyke is weathered and as a result of this, a strong incision into the basement rocks can be clearly seen on aerial photographs.

1.5.2 ALTERED BASEMENT

Laterite (Czl)

Numerous sea level and climatic changes during the middle Eocene have contributed to the development of extensive lateritic profiles in the study area (Hall and Kneeshaw, 1990). All basement rocks can be found in various weathered states.

The weathered BIF retains its structure and appearance, however it is usually deeply oxidised magnetite to martite.

The extent of dolerite weathering is largely dependent on the grain size of the rock. The coarse grained dolerites are highly susceptible to weathering and rarely crop out. Weathered products are found as part of some of the younger units described later. The medium grained dolerite sills are less susceptible to weathering. Saprolite is developed as the first stage of the degradation of the fresh rock. The majority of the parent rock crystal structure remains as relics with minor white to yellow areas of discolouration. The saprolite may be greater than 100 m thick.

A mottled zone exists above the saprolite, and is between 1 and 5 m thick. The mottled appearance is due to the decomposition of relic igneous crystals, leaving irregular concentrations of iron oxide and clay minerals. Pesoids and peloids develop above the mottled zone. The top of this zone may be cemented by goethite. The uppermost unit of the weathering profile is usually a soil profile, which typically is less than 1m thick. The physical appearance of the source rock will be significantly altered and only the chemistry of this soil will bear any relation to the original parent igneous rock (Youngman, 1997).

Basal gravel (Czr) or Basal Conglomerate (BCC)

This Tertiary conglomerate is believed to be laterally equivalent to the Hematite Pebble Conglomerate found on the surface at the Junction deposit (Hall and Kneeshaw, 1990). The conglomerate is generally 1 m to 2 m thick with a maximum thickness of 12 m. The base is often marked by a well-rounded, cemented, hematite pebble conglomerate. Other parts of this unit are typified by angular, poorly sorted clasts of BIF, chert and shale in a yellow-white clay matrix. The uppermost part of the basal gravel is occasionally silicified (Hall *et al*, 1990).

1.5.3 CHANNEL IRON DEPOSIT (CID)

The iron deposits in the palaeochannel are early Tertiary (Hall *et al*, 1990), chemically enriched talus and fluvial deposits. The CID is up to 70 m thick and consists of iron oxide spheroids that have formed in the palaeochannel. These ooids are mostly less than 2 mm, but range between 1 mm and 6 mm in diameter. Ooids have formed by chemical precipitation of hydrated iron oxides around hematite nuclei. The rims are frequently composed of goethite and the matrix between the ooids is a mixture of goethite, limonite and ferruginised wood fragments. The CID is divided into two parts; a clayey Basal zone and an upper Pisolite Zone. This upper Pisolite Zone is the economic deposit (Youngman, 1997).

Basal zone of the Channel Iron Deposit (Czp)

Overlying the Basal Conglomerate is the basal zone or Limonite-Goethite Channel (LGC), which may be as thick as 20 m. This zone ranges from 45 wt% to 57 wt% iron, depending on the degree of secondary mineralisation, pisolite development and clay content (Hall *et al*, 1990). Clay content and pisolitic structure generally increases towards the top of the unit. The top 1 m to 5 m of the unit has a clay cap, which is sometimes seen as a pebble conglomerate in a clay matrix, or a massive vitreous goethite horizon.

Main pisolite zone of the Channel Iron Deposit (Czp)

This zone varies in thickness from 40 m to 70 m and constitutes the economic iron ore body. The ore grade averages 56 wt% to 59 wt% iron and decreases as the ore becomes more weathered towards the top of the deposit. The unit is divided into two parts; the bottom high-grade ore (GVL), and the lower-grade ore (GVU).

1.5.4 OVERBURDEN MATERIAL

Overburden of up to 20 m thickness overlying the ore body will be removed prior to mining and stockpiled nearby, ready to be backfilled. The overburden is a mixture of lateritic pisolite, poorly sorted angular to sub-rounded BIF, chert and dolomite gravels in a sandy matrix. The gravels are referred to as the alluvial or colluvial gravels.

Weathered Channel Horizon (WCH)

Overlying the main ore deposit is a weathered zone consisting of pisolitic structures similar to the main deposit with a relatively low iron content between of 40 wt% to 54 wt% iron. The maximum thickness of the unit is 12 m and it contains various amounts of clay. Jointing is well developed within the zone as a result of diagenesis. Solution channels and desiccation shrinkage are well developed. Joints are generally lined with 1mm to 10mm of vitreous goethite and can be filled with any combination of yellow earthy limonite, opaline silica and soil washed from the surface. Close examination of sectional exposures of the WCH show evidence of sedimentary structures and reworking of the upper surface by flooding of the creek (Youngman, 1997). Hall *et al.* (1990) refer to the WCH as laterite.

Kaolin clay bands and pods occur throughout the WCH and occasionally in the CID. The bands are discontinuous and can rarely be correlated between sections 400m to 500 m apart (Hall *et al*, 1990). A band 6m thick exists near BHP's Eastern deposit. The same clay band is preserved in depressions at the Junction deposit and is referred to as the Eastern Clay Conglomerate (ECC used in this report) or Eastern Clay Horizon (Cze).

Photo by S Gardiner

FIGURE 1.4

PHOTOGRAPHIC SECTION SHOWING THE OVERBURDEN

Weathered Channel Horizon (WCH) aprox. scale 1 m

Eastern Clay Conglomerate (ECC) aprox. scale 3 m

Alluvium (ALL) aprox. scale 0.5 m

Photos by S Gardiner

Figure 1.5

PHOTOGRAPHS OF THE STOCKPILED OVERBURDEN

Oakover Formation (Czk)

This Formation has been observed at a number of localities along the channel. It comprises of a duricrust that varies from a chalky calcrete to an opaline silcrete (Youngman, 1997). One mechanism of formation may be as a product of the weathering of the Wittenoom Dolomite from outcrops located in the upper reaches of the drainage system. Another possibility is that pooling of water with high alkalinity or silica content caused precipitation of carbonate or siliceous duricrust. According to Youngman (1997), this pooling was aided by capillary action through the soil.

Cemented Alluvium (Cza)

Only a single outcrop has been mapped along the Yandicoogina Creek. The unit is a fluvial calcrete similar to the Tertiary Colluvium described below.

Tertiary Colluvium (Czc)

The Tertiary Colluvium is an imbricate gravel of sub-rounded to rounded, disc-shaped clasts with very few cobbles and boulders. This colluvium unit has been mapped at only one location at the Junction deposit.

Eastern Clay Conglomerate (ECC)

The ECC is physically similar to a mottled zone of the WCH and in the past was mapped as part of the WCH. This unit is preserved only in depressions in the CID, and overlying some BIF, suggesting that the unit covered low lying areas prior to reactivation of the Yandicoogina drainage system in the early Quaternary.

Alluvium (Qa)

Alluvium follows the present day drainage and has been transported by various creeks. The composition of the unit is sands, gravels and cobbles that have been eroded and transported to the bottom of the valley (Youngman, 1997).

1.6 DEVELOPMENT AND ENRICHMENT OF THE ORE DEPOSIT

This section summarises the ore genesis and palaeoenvironments described by Hall et al. (1990) for the Yandicoogina CID.

The Yandicoogina Syncline forms part of the Hamersley Range which was created about 135 Ma ago. This hosts the drainage system in which the present-day Marillana Creek flows. Vegetation covered the area, and would have been similar to savanna desert areas seen in Africa today (Hall *et al.*, 1990).

From the Palaeocene to the Early Oligocene, the climate in the Indian Ocean was equitable, due to a small difference in temperature between the poles and the equator. No ice cap existed during this period and conditions were generally warm (Hall *et al.*, 1990). The initiation of continental rifting of Gondwanaland formed an opening of a marine channel along the south west coast of Western Australia and together with the warm climate was largely responsible for a humid climate during the Eocene warm (Hall *et al.*, 1990). During this warm humid period extensive laterization of the basement rocks occurred. Fluctuations of sea level caused marine transgressions that effectively raised the base-level of erosion choking the incised drainage channels. Leaching of soluble silica and carbonate together with hydration of the iron ooids effectively created the CID. These processes contributed to the Hamersley

Iron Province palaeochannels being filled with limonitic and pisolitic goethite during Eocene times (Hall *et al.*, 1990). Sub-angular shaped clasts in the palaeochannel indicate that the material travelled only a short distance.

The late Eocene to early Oligocene saw a global drop in temperatures, causing the formation of polar ice caps and a lowering of sea level. The lowering of sea level caused the creek to incise deep into the basement rocks (Hall *et al.*, 1990).

Groundwater flowing in the palaeochannel is believed to have been of low pH from abundant humic acid and iron-saturated (Hall *et al*, 1990). Headward erosion commenced in onshore areas and continued until the early Miocene, when global temperatures rose once again. The iron started to precipitate as hematite and goethite. The precipitation continued forming concentric rings. This secondary mineralisation finally resulted in the pisolite CID that exists today.

Rising temperatures in the early Miocene caused a rise in sea level. These conditions resulted in the formation of calcrete and clay during the middle Miocene.

During late Miocene times, global temperature fell once again, resulting in a lowering of sea level and renewed onshore erosion. Arid conditions returned and prevail today. The overlying gravel deposits reflect the aridity (Hall *et al*, 1990).

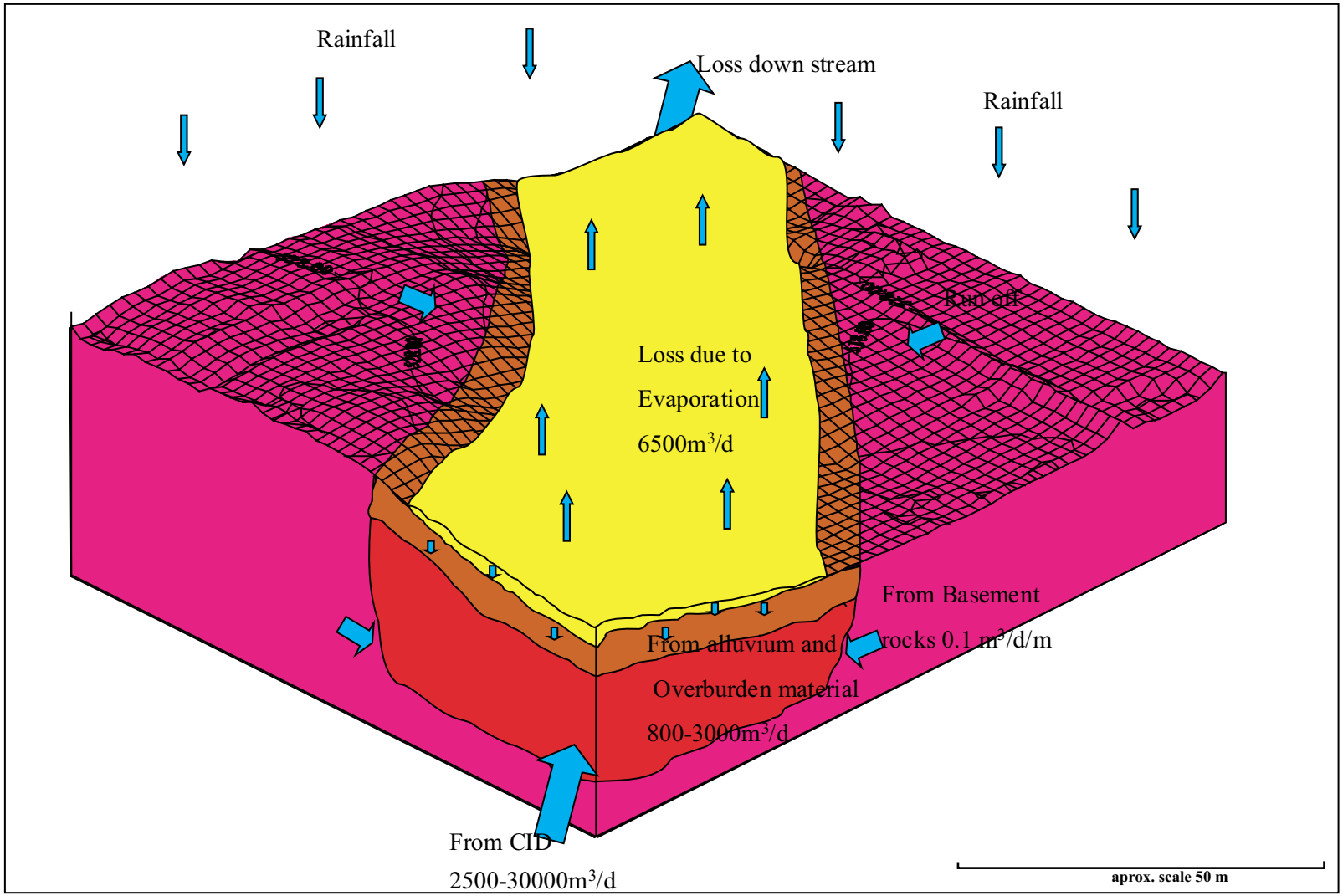


Figure 1.6

BASIC HYDROGEOLOGY OF THE MINE AREA

1.7 MINERALOGY OF THE CID

Optical microscopy investigations together with visible and near infrared (VNIR) spectroscopy research by the CSIRO suggested that significant proportions of hematite are present in the CID.

1.8 SURFACE DRAINAGE

The drainage system is controlled by the Yandicoogina syncline. The result is an east-trending drainage basin with the Hamersley Range to the north. The gradient of the basin is 1.5 m/km. Two major creeks provide drainage, the Marillana Creek and the Weeli Wolli Creek (Figure 1.2). The Marillana Creek has a catchment of 2,250 km^2 and drains into the Weeli Wolli Creek, which has a separate catchment of 1,750 km^2. The Weeli Wolli drains north into the Fortescue River via the Fortescue Marshes to the north of the Hamersley Ranges. Intermittent rainfall has resulted in a dense network of tributary streamlines, shallow soils and sparse vegetation (Hamersley Iron Pty Ltd, 1995).

The Marillana Creek has two smaller tributaries, the upstream tributary Phils Creek and the downstream tributary Yandicoogina Creek, with catchments of 100 km^2 and 200 km^2 respectively (Hamersley Iron Pty Ltd, 1995).

BHPIO (1995) showed that the Marillana Creek contributes less than 10 % of the total surface water into the Fortescue Marshes. This calculation is based on water flow data from 1985 to 1993 from the Water Authority of Western Australia (WAWA). It is noted however that due to the localised nature of the intense rainfall events, the Marillana Creek system could at times produce 100 % of the surface water into the marsh. However, this is unlikely and data between gauging stations in the Marillana Creek and the Weeli Wolli Creek show a reasonable correlation of flows with 71 % greater flow in the Weeli Wolli Creek (Hamersley Iron Pty Ltd, 1995).

The creeks are dry for most of the year and flow is highly ephemeral. Peak flow occurs within 24 hours of a rainfall event, and stream flow can continue for several days (Hamersley Iron Pty Ltd, 1995). The surface waters pass over and through a variety of rock materials such as the basement rocks and their products: BIF, dolerite and shale. Drainage continues into the valley where the waters percolate over and through alluvium, colluvium gravels, some clays, pisolite, calcrete and silcrete.

Table 1.2 **Catchment areas of creek systems in the province.**

Catchment	Approximate Area (km^2)	Streamflow (10^6 m^3/yr)
Marillana Creek	2,250	4.0
Phils Creek	100	-
Yandicoogina Creek	200	-
Weeli Wolli Creek	4,100	6.0
Fortescue River	17,200	42.2

Note: – no data available. (BHPIO, 1995)

1.9 HYDROGEOLOGY

The hydrogeology of the area has been intensively investigated by CSR, AGC Woodward-Clyde Pty Ltd for BHP and by A J Peck and Associates for Hamersley Iron. This work continues to provide data for long term hydrogeological management strategies.

The recharge and loss of water for the CID system is summarised below and shown in Figure 1.6.

- Recharge from Marillana Creek, where the CID is overlain by creek alluvium.
- Recharge directly from rain and surface runoff during the wet season.
- Recharge seepage from basement; water moves through fractures into the more hydraulically conductive CID.
- Loss through evapotranspiration from creek pools and vegetation.

1.9.1 AQUIFERS

Three main aquifers exist in the Hamersley Iron Province:

- Basement rocks
- Channel Infill Deposit
- Alluvium/colluvium

The hydraulic properties of these aquifers are summarised in Table 1.3.

Table 1.3 **Hydraulic factors of the CID system**

Parameter	Basement Rocks	CID	Alluvium
Hydraulic conductivity	na	10 - 100m/d	1000 - 10,000 m/d
Storativity	0.001 - 0.07	0.001 - 0.003*	0.4
Leakage to CID	0.1 m^3/d/m	na	800 - 3,000 m^3/d
Hydraulic Gradient	-	0.0025	0.0025
Transmissivity	740 - 1,100 m^2/d	-	-
Rainfall		180 - 350 mm	
Evapotranspiration		CID system 6500m^3/d	
Throughflow	na	2,500 - 3,000 m^3/d	2,500 m^3/d

*Note: - no value available, na not applicable, * confined storativity. Table compiled from selected data from Peck 1998 and Hamersley Iron 1995 reports. Storativity and Hydraulic Gradient are ratios and are unitless.*

Basement rocks

Limited testing of the basement rocks has shown that they are generally impermeable and considered to yield little or no water (Hamersley Iron Pty Ltd, 1995). The hydraulic conductivity is thought to be low and estimated values of transmissivity of

30 m^2/d and a specific yield of 0.01 were reported by BHP (BHPIO, 1995). Nevertheless, Peck (1998) suggested that the basement rocks are capable of providing significant yields of water through fracture systems. Test pumping in fractured siltstone and chert to the west of the Junction deposit indicated the basement may have a transmissivity of 740 to 1100 m^2/d and a storativity of 0.001 to 0.07.

There is thought to be some hydraulic conductivity between the basement rocks and the CID by leakage and this has been estimated at 0.1m^3/d/m (Peck, 1998).

Channel Iron Deposit

The CID is the main conduit for regional groundwater transportation. The aquifer is over 80 km long, 50 m wide and up to 80m in thickness. Numerous joints and solution cavities provide the high hydraulic conductivity. Irregular clay bands of various thicknesses give rise to a heterogeneous aquifer, with a large variation in airlift water yields from boreholes.

Long-term pumping data show that the CID acts as a fractured rock aquifer with a hydraulic conductivity of 10 to 100 m/d and a confined storage of 0.001 to 0.003. Drainage tests show that in the future the CID will respond as an unconfined aquifer with a storativity of 0.03 to 0.04 (Peck, 1998).

The throughflow has been calculated from a hydraulic conductivity cross sectional area to be 2,500 to 3,000 m^3/d (assuming an average hydraulic gradient and groundwater level). During cyclonic events the water table will be significantly elevated and allow a far greater throughflow (Peck, 1998).

Alluvium/colluvium

The alluvium/colluvium is between 150 m to 400 m wide with a maximum thickness of 20 m. The stratum consists of variably sorted mixtures of gravels, sands, silts and clays. The hydraulic conductivity has been calculated on the basis of the particle size and sorting and is considered to be about 10 m/d with a storativity of 0.2 (BHPIO, 1995).

Test pumping in the alluvial sediments of the Marillana Creek show that the upper 2 m of the coarse sediments have hydraulic conductivity between 1,000 to 10,000 m/d with an expected storativity value of 0.4 (Peck, 1998). Assuming a hydraulic conductivity of 5,000 m/d, thickness of 2 m, width of 100 m and hydraulic gradient of 0.0025 (same as the creek bed) the throughflow of the groundwater following a creek flow event was calculated to be 2,500 m^3/d. This value is comparable with the CID following a creek flow event.

Leakage from the alluvium and colluvium to the CID has been estimated to be between 800 and 5,500 m^3/d but is unlikely to exceed the 3,000 m^3/d throughflow of the CID (Peck, 1995)

Dewatering of the Eastern Deposit in the CID by BHP started in 1991. This was necessary as the majority of the CID lies below the water table. The groundwater was discharged further downstream of the Eastern Deposit at an estimated rate of 10,000 m^3/d. In 1997 this output was increased to 25,000 m^3/d with the

commencement of the dewatering of the BHP Central Deposit. The discharge has resulted in a rise of the groundwater level at the Junction deposit.

Loss due to evapotranspiration in vegetated areas of pooling has been calculated to be in the range of 5,000 to 9,000m^3/d with the most likely value to be 6,500 m^3/d (Peck, 1998).

1.10 WATER QUALITY

Water quality data for the Marillana Creek and the regional groundwaters are shown in Tables 3.1 – 3.3. The quality of the water in the region is potable. The Australian and USEPA guidelines for potable water are shown in the appendix.

The water in the area is weakly acid or slightly alkaline, and is typically of calcium/magnesium bicarbonate to sodium carbonate as shown in the Piper diagrams Figures A.1 –A.4 in the appendix.

The historical hydrochemical data can be found in the appendix.

1.11 MINING PROCEDURE

Dewatering commenced in 1998 and will be required throughout the mine's life. The groundwater is discharged into the Marillana Creek downstream of the mine at two locations near the Yandi Creek Junction shown in Figure 1.2. The discharge recharges the CID down gradient of the mine and maintains the flow of water downstream.

Mining started near the northern apex of the Yandi loop, and is progressing south west along the CID. The operation is conducted in sections by blasting and open cast mining down to a maximum depth of 70m.

Some waste rock will be used for bunding around the mine site, the remainder will be stock piled. As section areas are completed the stock piled material will be used to backfill the voids. Once the western limb of the loop has been mined the eastern limb will be mined using the same strategy. The volume of waste material is expected to increase by 33% as the material is broken up.

1.12 MINE CLOSURE PLANS

The closure plans for the Yandi mine may follow either of four directions. The final closure plan may be a combination of these. The plans have been discussed by Peck in the draft report - Hydrological Review for Yandi (HIY) Mine Closure Plan (1998) and are summarised below. The models are simplified and TDS values assume that secondary precipitation will not occur. However precipitation of secondary minerals is likely.

1.12.1 MINIMUM FINANCIAL COST PLAN

The most cost-effective direction is one in which once all the ore has been removed, there is no further backfilling of the pit. This would leave the area with two lakes, one by the southwest junction between the CID and the creek and another at the southeast junction. The level of the water in the lakes will predominantly be controlled by evaporation; thus the final surface area of the lake is critical to the final water balance. The surface area of the lakes would be controlled by the groundwater level, which would vary with the seasons and mining discharge.

If the water balance of the lake water is not managed, evaporation could become greater than the inflow. Hydrogeological monitoring and management would continue after mine closure to avoid a reversal of the current water flow.

The water entering the lakes would be of two types:

- groundwater with a TDS between 400 to 600 mg/L,
- surface runoff water with a very low TDS.

With continual evaporation, the lake water TDS would increase to 70,000 mg/L (Peck, 1998). The eventual result, after possibly 100 years, may be that the lake water would become so dense that it would not mix with the inflowing fresher water and might form a hypersaline layer at the bottom of the lake. This saline layer would begin to move out of the lake and into the groundwater system, diminishing the water quality of the aquifer. Pecks model shows that the saline wedge developed would reach the Waterloo bore area after 1000 years (Peck, 1998).

1.12.2 SURFACE WATER MANAGEMENT PLAN

This option involves a narrow channel built into the CID to facilitate water flow and to manage the transmissivity of the CID loop. Two lakes would exist as in the first plan. This option would provide easy passage of groundwater through the loop. The effect of evaporation would be less significant and the final TDS in the pit lakes would be 42,000 mg/L (Peck, 1998).

1.12.3 MAXIMIZATION OF WATER INFLOW

By redirecting water from the CID and the creeks into the lakes, the TDS of the lake water could be reduced to 3,900mg/L. The salinity of the pit lakes would not be expected to stabilise for 1000 years. A saline layer would still eventually develop. This option would significantly reduce the level of the groundwater and alluvium waters downstream of the pit (Peck, 1998).

1.12.4 ISOLATION

This option isolates the waste area from the creek and the CID by forcing the flow along the Marillana Creek rather than allowing it to flow along the CID (Peck, 1998). The viability of this option would depend on the availability of clay from the waste rock. If there was enough clay it could be used to bund around the perimeter of the backfilled waste. It is known that in parts of the CID there are 10m thick clay beds, though it is not certain any are in the Yandi loop area. The flow from the CID would be redirected from the mined area along the Marillana Creek and back into the Marillana Creek and the CID at the Yandi junction further downstream.

The pit lakes would become salt pans in the dry season and hypersaline during the wet season. There would be no outflow, so there would be minimal environmental effects downstream of the pit. During the dry season Peck (1998) predicts that 50% of the alluvium water would be lost to evaporation. The TDS in the alluvium waters would also rise during the dry season. These salts would be flushed away during the wet season.

An advantage of isolation is that the potential environmental impact of potential leachate from the overburden waste would be minimised.

1.13 EFFECTS OF BACKFILLING ON TRANSMISSIVITY

Models to predict the hydrogeology of the CID have used hydrogeological values of the existing CID environment. After excavation and backfilling the CID will have very different hydrogeological properties. The transmissivity can be estimated using results from grain size analysis or permeability tests in the laboratory.

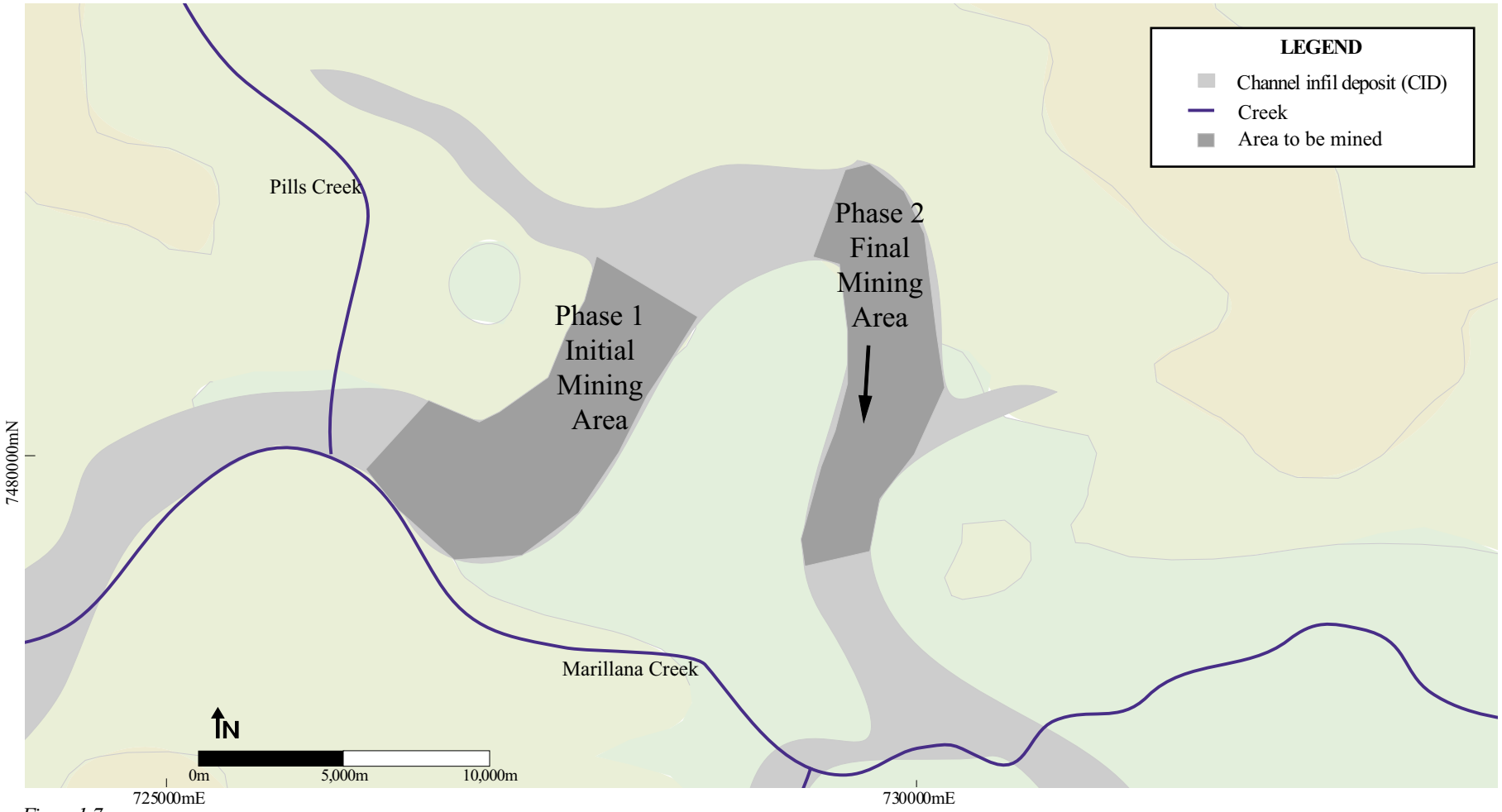
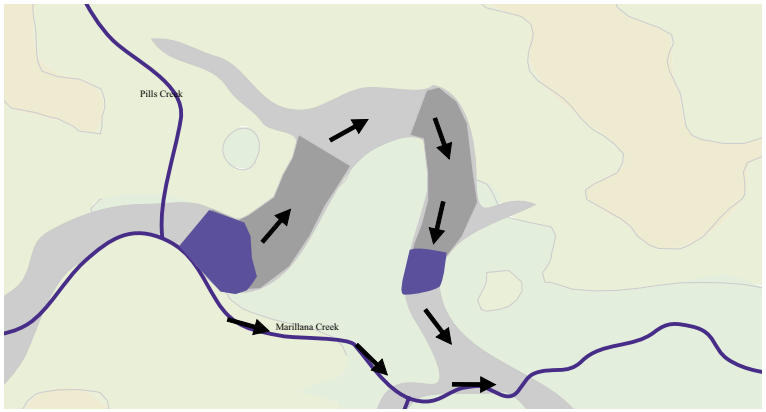
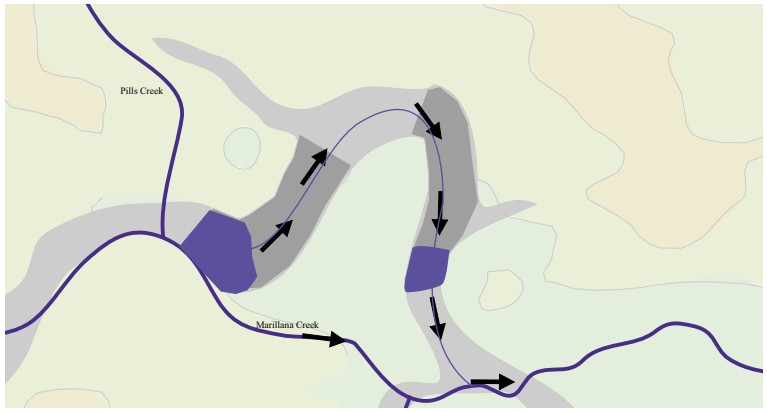


Figure1.7

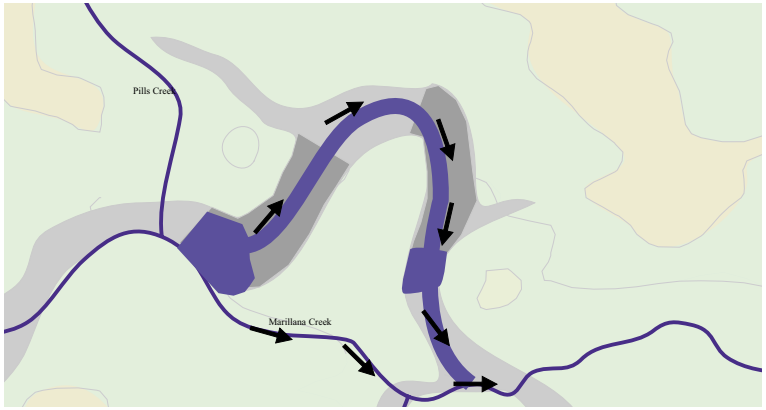
DIRECTION OF EXCAVATION FOR MINING IN PHASE 1 AND 2



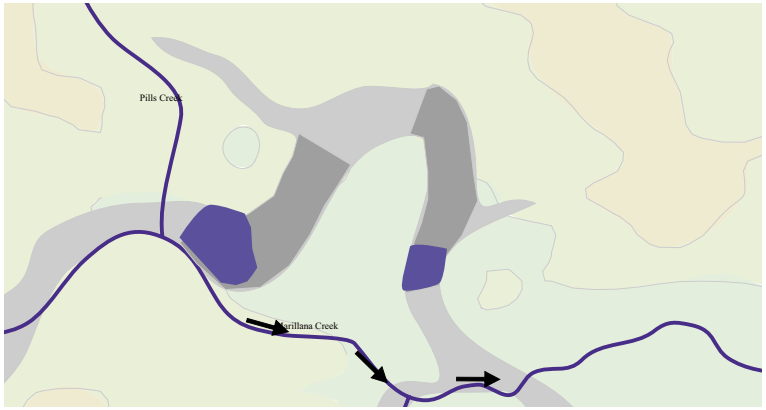
MINIMUM FINANCIAL COST PLAN



SURFACE WATER MANAGEMENT PLAN



MAXIMIZATION OF WATER INFLOW PLAN



ISOLATION PLAN

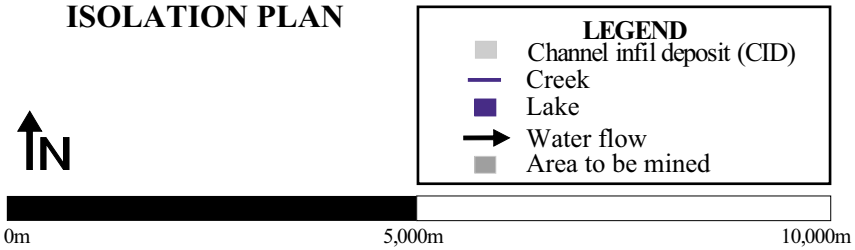


Figure1.8

FOUR POSSIBLE CLOSURE PLANS

Chapter Two
METHODOLOGY

2.1 INTRODUCTION

This chapter describes the methods used in the laboratory analyses of the various samples. Topics include planning, collection, testing, calculations and the quality control processes used during the investigation.

2.2 BACKGROUND RESEARCH

The objectives of the project were to determine the current water quality and to predict future water quality at mine closure. The second objective was to estimate the physical properties of the groundwater system after backfilling.

Reports and papers covering the chemistry and geology of regional waters and rocks were studied (See Chapter One). This was to establish the background of the region and gain an insight into geological, hydrogeological and chemical processes of the area. A review of several leaching experiments was conducted to assist in the design of an experiment to measure the affect that the waste rock could have on the hydrogeology and chemistry groundwater.

Environmental effects of several chemical elements were studied to determine which elements the project should focus on.

2.3 FIELD WORK AND SAMPLE COLLECTION

2.3.1 WATER SAMPLES

Hamersley Iron collected 26 ground and surface water samples from the region. The groundwaters were sampled using a Grunfos pump. Three bore volumes were removed from the bore prior to the sampling. The sample pH and TDS was recorded. Two aliquots were left unpreserved. The sample number, date and location were written on each sample and recorded in the sample record file. The waters were transported to MPL in a cool box. As part of the 1998 sampling program duplicate samples were also sent to Curtin University for analysis. The locations of the samples are shown in Figure 2.1.

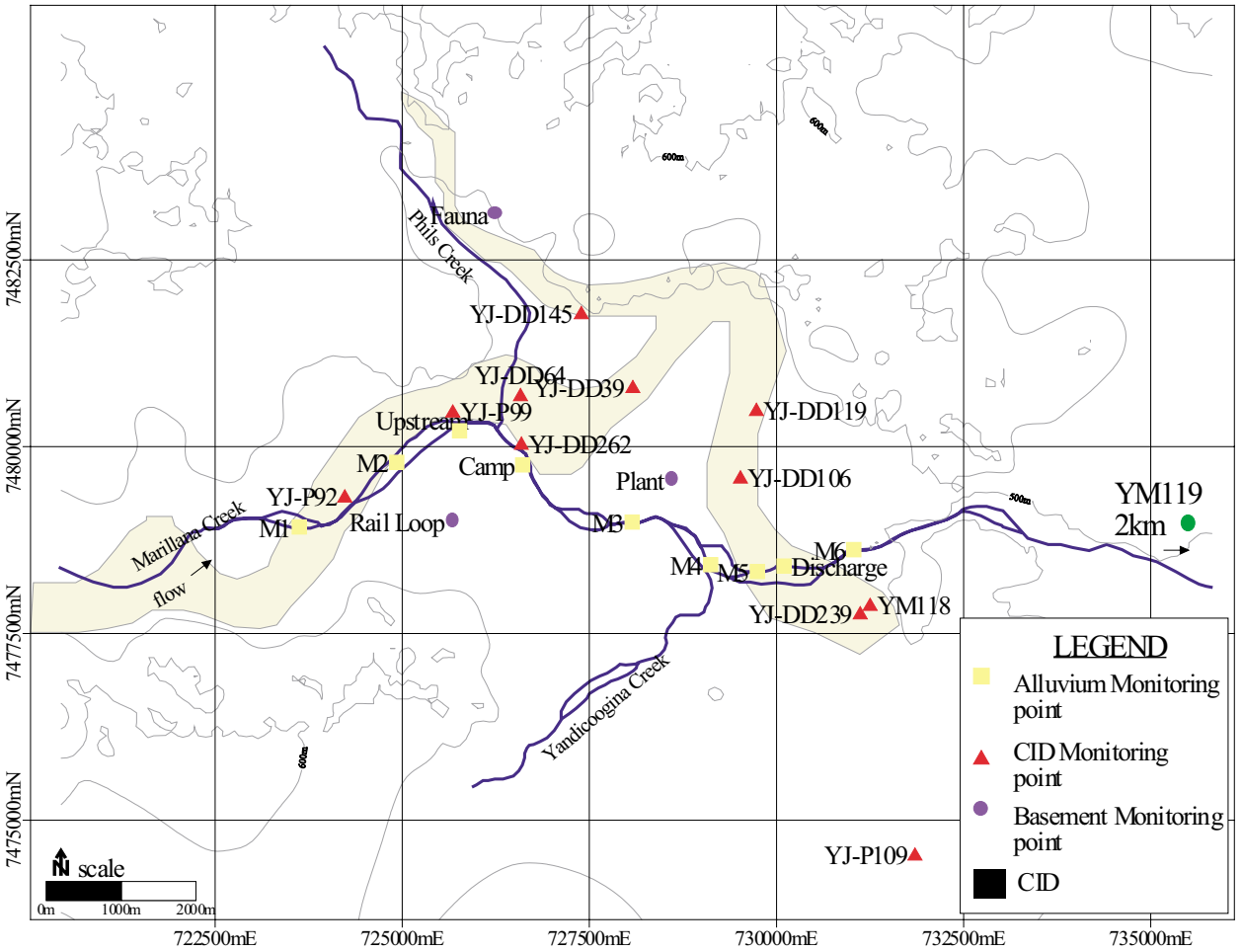


Figure 2.1

LOCATION OF WATER SAMPLES FROM THE YANDI REGION

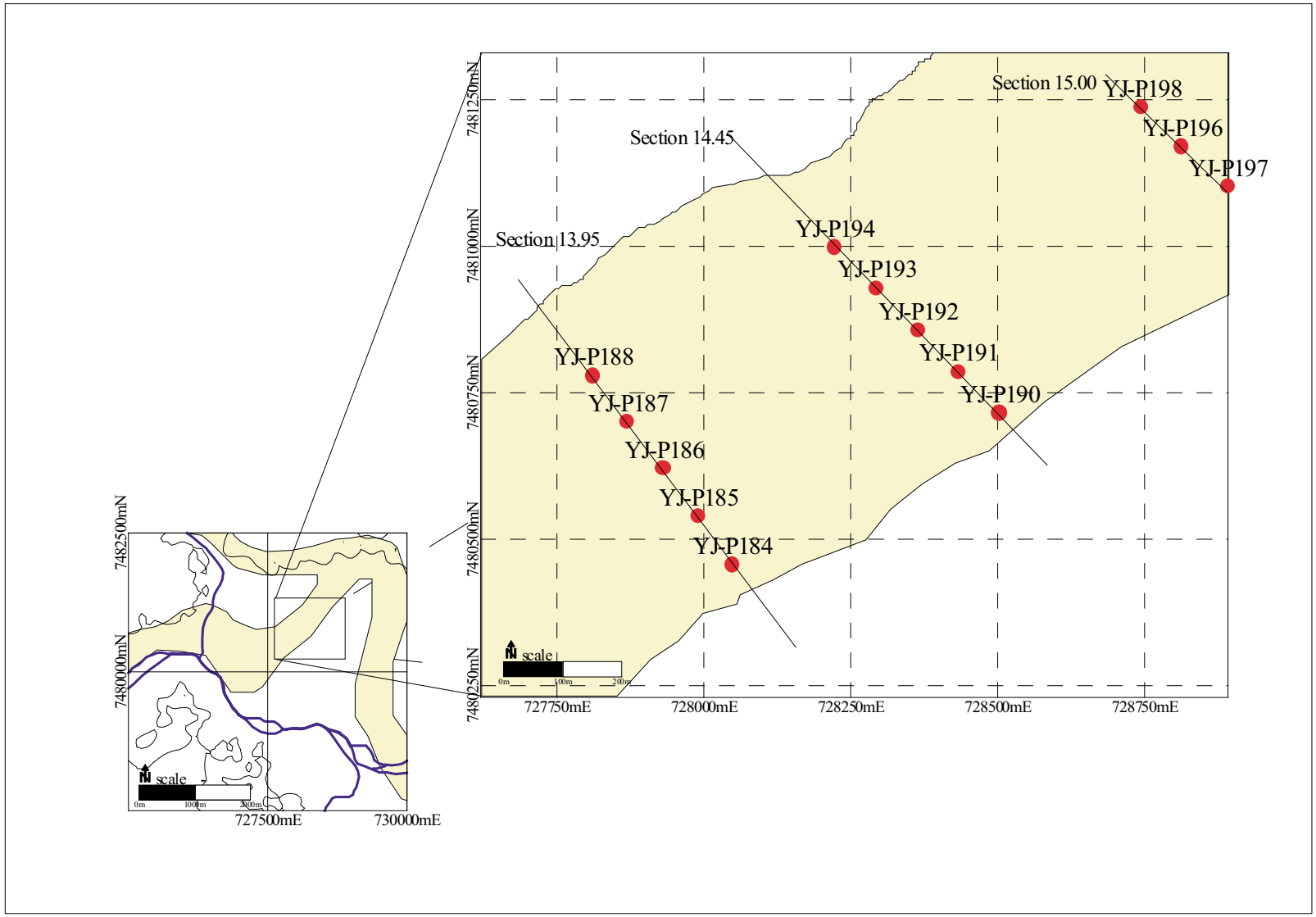


Figure 2.2

LOCATION OF OVERBURDEN ROCK SAMPLES

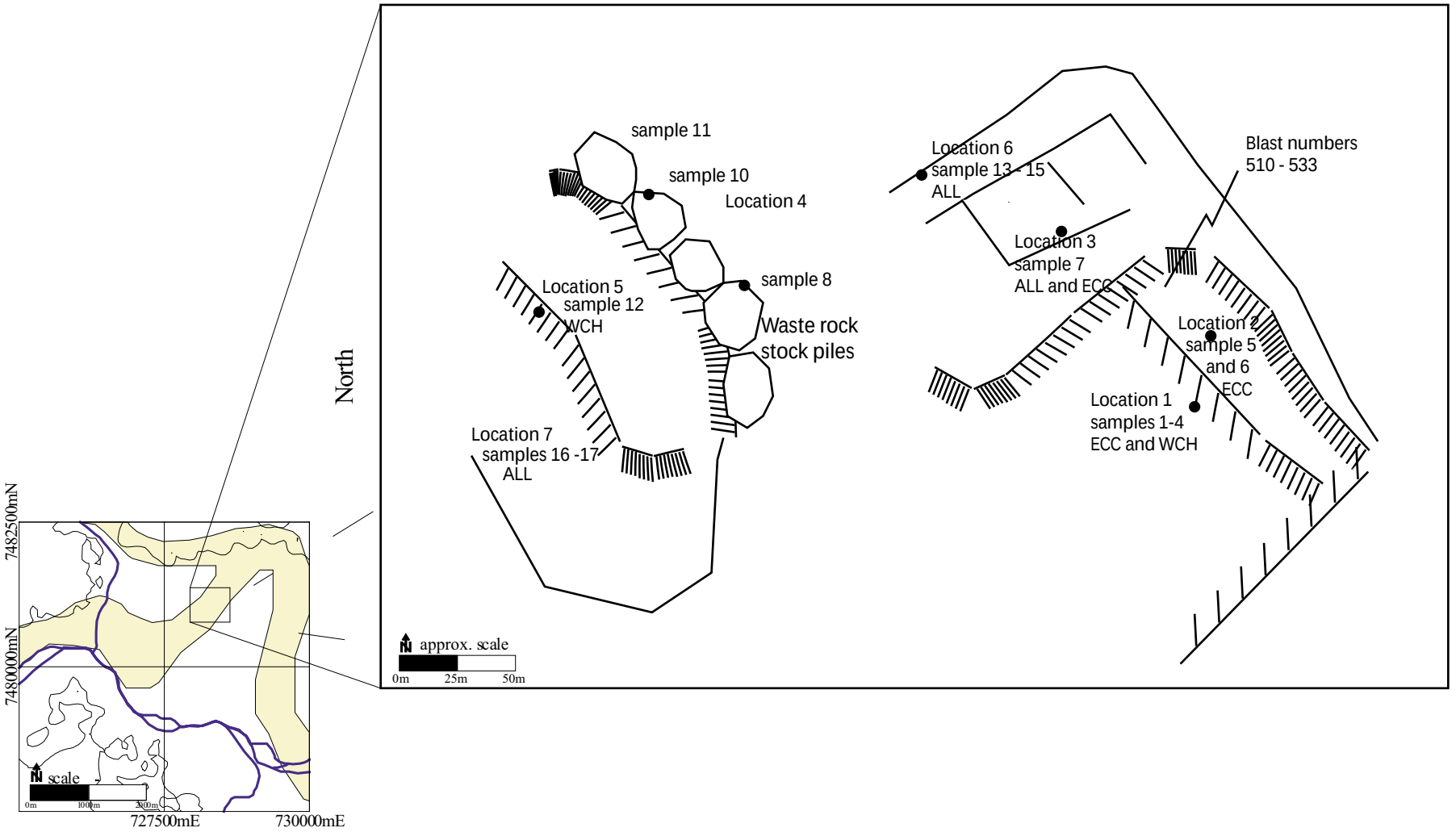


Figure 2.3
SAMPLE LOCATIONS OF THE BULK ROCK SAMPLES

2.3.2 ROCK SAMPLES

Rock samples were initially collected from three sections of the 1995 CRA drilling program (Figure 2.2). These samples were collected using percussion drilling methods and were stored at a Hamersley Iron warehouse prior to preparation and analysis. The samples chosen for this study represent the Alluvium, Eastern Clay Conglomerate and the Weathered Channel Horizon overburden material found in the CID.

In October 1999 bulk samples were collected for hydrogeological testing. These samples were representative of the physical properties of the overburden materials. The three main overburden rock types were sampled. Samples were taken from various parts of the pit and from the stockpile area (Figure 2.3). Sample numbers, date and locations were written on each sample and recorded in the sample record file. These samples were then couriered to the School of Applied Geology, Curtin University for analysis.

2.4 SAMPLE PREPARATION

2.4.1 WATER SAMPLES

On receipt of the waters, sample identifications were made and each sample was divided into three aliquots. The first aliquot was for general analysis. The second aliquot was filtered through a 45 μm pore size membrane filter, labelled and stored in a refrigerator prior to anion analysis. The last aliquot was filtered then acidified to reduce the pH value to < 2. The acidification ensured that no precipitation of analytes would occur during storage. The samples were stored in the refrigerator at 4°C prior to analysis.

2.4.2 ROCK SAMPLES

The rock samples were crushed to gravel size, then coned and quartered to produce a smaller, homogeneous analytical sample. Samples then crushed to a fine powder (<200 mm) using a tungsten carbide Tema® mill. The powders were transferred to plastic containers, sealed and labelled with the relevant sample number.

The 5g analytical sample of rock powder was digested in a 50 mL mixture (4:1) concentrated nitric: concentrated perchloric acid at 230°C, with the addition of a further 1 part of concentrated hydrofluoric acid after 3 hours. The sample was then evaporated to dryness. The residue of the digest was dissolved in 2 ml concentrated nitric acid and 1mL concentrated hydrochloric acid at 100°C for 2 hours. The final residues were made up to a volume of 50 ml with 2% nitric acid. These solutions were then decanted into tubes ready for the analysis for cations, trace metals and rare earth elements. Blanks and duplicates were also prepared using this method. A 2ppb rhodium and iridium spike was then added as an internal standard.

2.4.3 LEACHATE SAMPLES

Two leachate tests were conducted. In the first, the powdered rock samples were leached with deionized water. The second more aggressive test used a sodium acetate/acetic acid buffer solution that had a pH of 4.85. Both methods were based on leachate tests devised by Francis, Maskarinec and Lee (1988) and used to simulate organic acid attack rather than sulphuric acid attack. This selection was made as all rock samples had very low sulphide values.

Water solvent 1:20 (solid:solvent)

Powdered rocks were placed into a plastic container with deionised water at a 1:20 weight by weight ratio. Samples were then shaken for 24 hrs, then filtered through a 45 μm filter membrane. The samples were divided into three aliquots then prepared for general, anion, cation, trace element and rare earth element analysis.

Sodium acetate/acetic acid buffer solvent 1:50 (solid:solvent)

Powdered rock was placed into a plastic container with sodium acetate/acetic acid buffer at a 1:50 weight by weight ratio. The sample was shaken for 24 hrs then filtered using 45 μm filter membrane. The samples were divided into aliquots and prepared for general, cation, trace element and REE analysis.

The leachate test were repeated with samples that had not been ground to rock powder to illustrate the difference that the final grainsize has on the rate of leachate extraction.

2.5 SAMPLE ANALYSIS

2.5.1 WATER AND LEACHATE ANALYSES

The waters samples were analysed for general chemistry, major anions, major cations, trace metals and REE. The analytical methods employed are discussed below.

General Chemistry

The pH, electrical conductivity and salinity were measured in the majority of water and leachate samples. Electrical conductivity, pH and salinity were measured using a small portable meter that was calibrated against commercially available standards prior to analysing each batch.

Alkalinity was determined by titrating 20 mL of the sample with 0.001 M sulphuric acid solution using a methyl orange indicator to detect the end point.

Major Anions

Common soluble anions were measured using high performance ion chromatography (HPIC). The instrument used was a Dionex® 4500I gradient ion chromatograph in the School of Applied Geology, Curtin University. The samples were eluted through a Dionex® AN-12A anion column using sodium bicarbonate eluent and a conductivity detector. This method can determine concentration of bromide, chloride, nitrite, nitrate and sulphate. The instrument was calibrated with a standard solution produced from commercially available standard solutions (Aldich Co Ltd). Peak areas were used to calculate the anion concentrations in the samples. Samples

greatly exceeding the standard value and/or likely to overload the analytical column were diluted then repeated.

Carbonate and bicarbonate were calculated using the alkalinity and pH.

Major Cations

Sodium, potassium, calcium, magnesium, iron and manganese were determined using atomic absorption spectroscopy (AAS), in the School of Applied Chemistry, Curtin University. The instrument was calibrated using a blank and elemental standards detailed in Table 2.1. Samples with analyte concentrations exceeding the standard of highest concentration were diluted and re-analysed. Each sample was analysed in duplicate.

For quality control purposes some samples were also analysed using HPIC using a Dionex® CS-12 cation column and sulphuric acid eluent.

Table 2.1 **Standard concentrations used during AA calibration (mg/L).**

Element	Standard 1	Standard 2	Standard 3	Standard 4
Na	0.25	0.5	1.0	1.5
K	1.0	3.0	5.0	6.0
Ca	1.0	3.0	4.0	5.0
Mg	5.0	10	15	20
Fe	2.5	5	7.5	10
Mn	2.5	5	7.5	10

Trace elements and rare earth elements

These elements were quantified using Inductively Couple Plasma Mass Spectrometry (ICP-MS). Claritas M.E. and Merck multi-element standards were used to calibrate the instrument. Calibration was done at the end of the sample set to avoid analytical train. Repeat QC standards or repeat samples were used to monitor drift. A 2 ppb rhodium and iridium spike in each sample was used as an internal standard.

2.5.2 ROCK ANALYSIS

Chemistry

Major elements were analysed by Hamersley Iron using X-Ray Fluorescence (XRF). Further analyses for trace elements and REE were conducted as part of this study using ICP-MS.

2.6 HYDROGEOLOGY

The aim of this project was to estimate the transmissivity of the aquifer prior to modification occurring as a result of backfilling. This was achieved by studying the hydrogeological reports of the area and conducting laboratory experiments.

Several methods were used to estimate the transmissivity of the modified aquifer. Laboratory tests on bulk samples were used to estimate the hydrogeological values. Three types of tests were employed:

- Constant head permeability test.
- Falling head permeability test.
- Grain-size analysis.

The head tests used Darcy's law:

$$Q = kAh/l$$

Where Q = flow
A = Cross sectional area
h = Change in head
l = Length of area

(Brassington, 1988)

The tests simulated what might happen in the real aquifer after backfilling. A column of uniform width was packed with the unconsolidated rock. The column was then saturated with water and the temperature recorded. The constant head test measured the permeability for a sample with a constant head of pressure and the falling head test measured the sample with a reducing head of pressure. Both tests monitored the volume of water output over time.

The hydraulic conductivity was calculated from the permeability value. To calculate the hydraulic conductivity accurately, factors such as the properties of the fluid were considered ie. density and viscosity (Kresic, 1997).

$$K\mathrm{i} = K\,\mu/\rho g$$

Where (Kresic, 1997)

K_i is the hydraulic conductivity
μ is the viscosity
ρ is the density
g is the acceleration due to gravity (9.81 ms^{-2})

2.6.1 CONSTANT HEAD TEST

The experiment was set up as shown in Figure 2.4. Water was added to the column at the supply point to give a head of pressure h. The water filtered through the perforated perspex layer and through the sample of cross-sectional area A and length L. The flow was calculated by measuring the volume of water collected over time t. This test was repeated with different heads of pressure.

There are different ways of calculating the permeability from these results. The method of least bias was the geometric mean of the sample's permeability at various heads of pressure.

$$\text{Geometric mean of } K = \Sigma(\ln(K))/n$$

Where
n is number of results

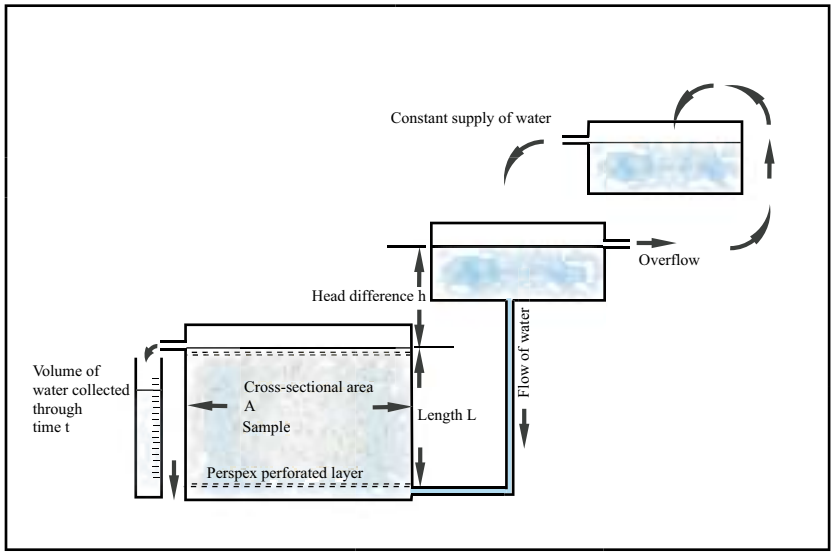


Figure 2.4

APPARATUS SET UP FOR CONSTANT HEAD TEST

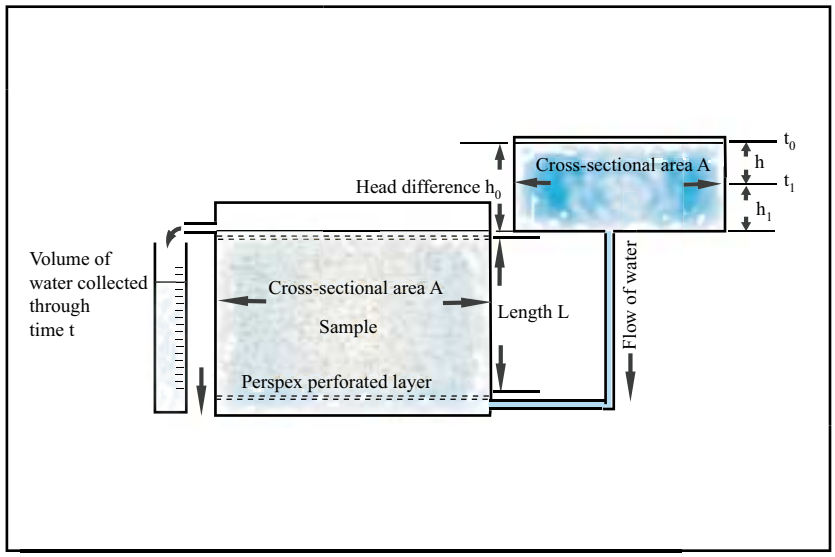


Figure 2.5

APPARATUS SET UP FOR FALLING HEAD TEST

2.6.2 FALLING HEAD TEST

The falling head test was the second method used to determine the permeability of the bulk rock samples and is shown in Figure 2.5. This method monitors the drop of water level in a container over time.

The test started at time t_0, with the head of water at height h_0. The new value of the head, h, was recorded at frequent time intervals. The test ended when the head of water had fallen to zero. The test was repeated several times for each sample.

The hydraulic conductivity was calculated by plotting a graph of the h_0/h_1 against time and a best-fit line was drawn. A point was chosen on the best-fit line and the transmissivity was calculated according to the equation:

$$K = r_b^2 L / r_s^2 t \ \ln h_0/h_1$$

(Kresic, 1997)

where

r_b is the radius of the container.
r_s is the radius of the sample.

2.6.3 GRAIN SIZE ANALYSIS

The final method to determine hydraulic conductivity used grain size distribution. There are three different equations employed to calculate the transmissivity depending on the distribution of grain size in the rock sample. Table 2.2 shows which equation should be used for a sample with a given distribution.

Table 2.2 **Grain size analysis equations used to calculate permeability.**

Equation	U	d_e (mm)	Description
Hazen, $K=g/v\ C_h f(n) d_{10}^2$	<5	0.1 to 3	Well sorted
Kozeny, $K=g/v\ C_k f(n) d_{10}^2$	<2	0.5 to 4	Coarse sand
Breyer, $K = g/v\ C_b d_e^2$	1 – 20	0.06 to 0.6	Heterogenous

Note U is uniformity, d_e is the effective grainsize.

The grainsize distribution was determined by the following procedure. Firstly, the dry rock sample was gently disaggregated. A known weight of the sample was sieved through a number of different size sieves. The weight of the sample that did not pass through each sieve was recorded and converted to a percentage of the total sample weight. The cumulative percentage against grain size was plotted on a semilog scale graph. The tenth (d_{10}) and the sixtieth (d_{60}) percentile values were used to calculate the uniformity (U) and permeability of the sample (Kresic, 1997).

The uniformity is:

$$U = d_{60}/d_{10}$$

Hazen method

The Hazen equation was used for sediments with a uniformity of less than 5 and an effective grainsize (d_e, which is equal to d_{10}) between 0.1 mm and 3 mm.

The formula for the Hazen equation is:

$$K = g/v\ C_h f(n) d_{10}^2$$

where:

$C_h = 6 \times 10^{-4}$

$f(n) = [1 + 10(n-0.26)]$ the function of porosity, n.

$g = 9.807\ m/s^2$ Gravity acceleration.

$v = 1.14 \times 10^{-6}$ the kinematic viscosity.

(Kresic, 1997)

Kozeny method

The Kozeny equation is applicable to course sand samples with a low uniformity of less than 2 and an effective grainsize between 0.5 mm and 4 mm.
The formula for the Kozeny equation is:

$$K = g/v\ C_k f(n) d_{10}^2$$

where:

$C_k = 8.3 \times 10^{-3}$

$f(n) = n^3/(1-n)^2$

(Kresic, 1997)

Breyer method

The Breyer equation does not express porosity as part of its formula and is therefore applicable to samples with a heterogeneous porosity. It is also the most appropriate equation to use for poorly sorted samples. The equation can be used for samples with uniformity values from 1 to 20 and effective grain sizes between 0.06 mm and 0.6 mm.

The formula for the Breyer equation is:

$$K = g/v\ C_b d_e^2$$

where:

$C_b = 6 \times 10^{-4} \log(500/U)$

(Kresic, 1997)

Each of the laboratory methods provided an estimate of the hydraulic conductivity for the immediate area from where the sample was taken.

2.7 QUALITY CONTROL

Several quality control procedures were used to ensure the quality of the final results. These procedures and calculations facilitated the identification of anomalous samples. Anomalous values were investigated and either reanalysed or not used in later calculations.

2.7.1 IONIC BALANCE

Water samples should be electrically neutral, ie have equivalent quantities of anions

and cations. The ionic balance for the majority of the samples was within 10 %. Samples with ionic balance greater than 10 % suggested that a significant component was not determined.

2.7.2 TDS BALANCE

Two calculation methods were used to compare the measured gravimetric TDS against a calculated TDS. The first method calculated TDS using the electrical conductivity obtained with the conductivity meter. The second method calculated the value of the sum of reduced cations, anions and neutral species measured by chemical analysis. These TDS values are compared in Table 3.28

2.7.3 ELECTRICAL CONDUCTIVITY

Most dissolved solids contribute to the electrical conductivity (EC) of a solution. Consequently a relationship between the two is expected. The measured TDS values were plotted against the measured EC. Values that were anomalous were investigated.

2.7.4 pH

The pH was studied in conjunction with the chemistry, particularly the alkalinity. Samples with a high alkalinity were expected to have a pH above 7.

2.7.5 DUPLICATE ANALYSIS

Duplicate analyses were compared. Where necessary, inconsistencies were studied further to establish why the values were different.

2.7.6 LABORATORY STANDARDS

Each leachate and rock analysis run included an internal laboratory standard. The laboratory standard was composed of an arbitrary BIF sample. The results of the laboratory standards were monitored to ensure that the results did not fall outside the expected laboratory error.

2.7.7 REFERENCE MATERIAL STANDARDS

Reference material standards were analysed during the ICP-MS rock analyses. These materials have been analysed by many other laboratories as part of an ongoing quality assurance procedure.

2.8 INTERPRETATION

Calculations to determine the saturation indices, evaporation models and inverse modelling were completed using PHREEQC (Parkhurst, 1995) code.

2.8.1 IONIC RATIOS

Ionic ratios were used to show changes in the water quality and used to determine if evaporation or other processes caused any changes.

2.8.2 CORRELATION ANALYSIS

The total rock digestion results were compared with each other using an MS Excel correlation tool. This tool compares the data sets and returns a positive value of 1 if the data sets are related to each other, a negative value –1 if the sets are inversely related, and zero if the sets are completely unrelated. Strong positive correlations are a good indication that elements occur together and are associated with the same mineral. A strong negative correlation would indicate that one element is depleted as another is enriched. The complete correlation results are shown in the appendix.
See below for the formula used to calculate the correlations.

$$r_{x,y} = \frac{Cov(X,Y)}{s_x s_y}$$

2.8.3 GEOCHEMICAL ABUNDANCE INDEX (GAI)

The GAI values express the degree of enrichment compared to the Earth's crustal abundance of an element (Thomas and Evans, 1998). The values are expressed as an integer between one and six. The relative enrichment factors are shown in Table 4.1.

2.8.4 GEOCHEMICAL MODELLING OF GROUNDWATERS AND PIT WATERS

Arithmetical methods and the computer code PHREEQC (Parkhurst, 1995) was used to try to estimate the behaviours of the groundwaters and pit lakes using the analytical results obtained. The limitations of the PHREEQC code are discussed in Chapter 5.

Chapter Three

LABORATORY RESULTS

3.1 INTRODUCTION

This chapter reports the results from the various laboratory analyses of water, rock and leachate samples.

3.2 WATER ANALYSIS

The hydrochemical characteristics recorded for the water samples in the field by Hamersley Iron environmental staff and at the laboratories of the Schools of Applied Geology and Applied Chemistry of Curtin University of Technology are listed below. Detection limited for some elements varied from lab to lab.

3.2.1 GENERAL CHARACTERISTICS

Electrical conductivity (EC), pH, Total dissolved solids (TDS) or salinity (by equivalent EC) and alkalinity (as $CaCO_3$).

3.2.2 MAJOR AND MINOR ANIONS

Bromide, chloride, fluoride, sulphate and hydroxide, bicarbonate and carbonate by calculation.

3.2.3 MAJOR CATIONS

Calcium, iron, magnesium, manganese, potassium, sodium and strontium.

3.2.4 NEUTRAL SPECIES

Total silicon.

3.2.5 NUTRIENTS

Nitrate, phosphate.

3.2.6 TRACE ELEMENTS

Antimony, arsenic, barium, beryllium, bismuth, cadmium, cerium, chromium, cobalt, copper, lead, mercury, molybdenum, nickel, selenium, silver, tellurium, thallium, thorium, uranium and zinc.

3.3 REGIONAL WATER QUALITY

Hamersley Iron first analysed the regional surface waters and groundwaters in 1992 and then from 1998 onwards. Figure 2.1 shows the locations from which the water samples were taken.

The results for the analyses of these samples are shown in Tables 3.1 - 3.3. In Table 3.1 are listed the results for the CID waters, the results for surface and alluvium waters are listed in Table 3.2 and the basement waters in Table 3.3. These results represent the water quality prior to the mining operations.

Table 3.1 **Hydrochemical characteristics of the groundwaters in the CID**

Hydrochemical characteristics	YJDD39	YJDD64	YJP99	YJDD106	YJDD119
Date	3/08/98	3/08/98	3/08/98	3/08/98	3/08/98
General characteristics					
pH	6.67	6.62	6.23	5.44	6.64
EC (Lab)(ms/m)	89	74	54	38	92
pH (Lab)	7	6.8	7.2	6.2	6.9
Salinity	434	361	227	84	449
TDS	350	320	240	240	440
TSS	<5	5	<5	<5	<5
Oil and Grease	<5	<5	<5	<5	<5
Major ions (mg/L)					
Sodium, Na	70.3	58.7	40.9	28.5	74.8
Potassium, K	7.5	5.3	3.9	4.0	10.7
Magnesium, Mg	44.7	31.8	21.7	15.3	47.2
Calcium, Ca	41.0	38.0	28.0	18.0	40.0
Iron(II), Fe	<0.5	<0.5	<0.5	<0.5	<0.5
Iron(III), Fe	-	-	-	-	-
Manganese, Mn	<0.2	<0.2	<0.2	<0.2	<0.2
Strontium, Sr	0.14	0.08	0.07	0.05	0.10
Fluoride, F	-	-	-	-	-
Chloride, Cl	73	86	45	46	83
Sulphate, SO_4	34	40	28	22	42
Bicarbonate, HCO_3	350	250	200	120	330
Carbonate, CO_3	<1	<1	<1	<1	<1
Neutral species					
Total silicon (as SiO_2)	-	-	-	-	-
Nutrients					
Nitrogen (total)	0.4	1.3	1.0	0.2	1.2
Nitrate (as N)	-	-	-	-	-
Trace elements (ug/L)					
Aluminium, Al					
Antimony, Sb	0.02	<0.01	<0.01	<0.01	<0.01
Arsenic, As	-	-	-	-	-
Barium, Ba	34.9	18.4	31.3	56.5	18.8
Beryllium, Be	0.59	0.11	0.14	0.13	0.19
Bismuth, Bi	<0.01	<0.01	<0.01	<0.01	<0.01
Cadmium, Cd	0.04	0.01	0.08	0.07	0.03
Cerium, Ce	0.02	0.07	0.07	0.10	0.10
Cobalt, Co	0.52	0.12	0.13	0.18	0.11
Copper, Cu	4.23	2.42	5.24	5.51	2.18
Lead, Pb	0.96	0.88	1.73	0.98	0.89
Mercury, Hg	0.35	0.28	0.24	0.28	0.22
Molybdenum, Mo	0.50	0.22	0.15	0.06	0.14
Nickel, Ni	1.65	0.97	0.64	0.63	0.42
Selenium, Se	2.94	2.41	1.88	0.74	1.78
Silver, Ag	<0.01	<0.01	0.02	0.02	0.01
Tantalum, Ta	<0.01	<0.01	<0.01	<0.01	<0.01
Tellurium, Te	11.01	<0.01	0.03	<0.01	0.02
Thallium, Tl	0.06	<0.01	0.01	0.01	0.01
Thorium, Th	0.01	<0.01	<0.01	0.02	0.01
Uranium, U	0.33	0.22	0.12	0.08	0.40
Zinc, Zn	2.93	1.87	1.66	4.15	1.11

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

Table 3.1(cont.) **Hydrochemical characteristics of the groundwaters in the CID**

Hydrochemical characteristics	YJDD239	YJDD262	YJP92	YJP109	Discharge Lagoon	Pool below camp
Date	3/08/98	3/08/98	3/08/98	3/08/98	3/08/98	3/08/98
General characteristics						
pH	6.68	6.61	6.64	6.95	6.58	7.24
EC (Lab)(ms/m)	82	-	-	-	-	-
pH (Lab)	7.1	-	-	-	-	-
Salinity	397	482	383	491	383	554
TDS	490	440	-	580	-	580
TSS	<5	10	-	5	-	<5
Oil and Grease	<5	<5	-	<5	-	-
Major ions (mg/L)						
Sodium, Na	67.0	74.7	66.1	71.0	68.7	115
Potassium, K	6.8	6.8	6.0	9.0	6.6	8.1
Magnesium, Mg	35.7	42.9	35.4	52.7	37.1	41.2
Calcium, Ca	42.0	50.0	42.0	57.0	43.6	52.0
Iron(II), Fe	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Iron(III), Fe	-	-	-	-	-	-
Manganese, Mn	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Strontium, Sr	0.09	0.11	0.08	0.08	0.08	0.10
Fluoride, F	-	-	-	-	-	-
Chloride, Cl	96	120	-	76	-	170
Sulphate, SO_4	33	45	-	47	-	57
Bicarbonate, HCO_3	280	280	-	410	-	320
Carbonate, CO_3	<1	<1	-	<1	-	<1
Neutral species						
Total silicon (as SiO_2)	-	-	-	-	-	-
Nutrients						
Nitrogen (total)	1.2	0.5	-	2.0	-	<0.1
Nitrate (as N)	-	-	-	-	-	-
Trace elements (ug/L)						
Aluminium, Al	-	-	-	-	-	-
Antimony, Sb	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
Arsenic, As	-	-	-	-	-	-
Barium, Ba	16.2	24.6	19.0	28.8	15.1	30.6
Beryllium, Be	0.18	0.20	0.18	0.21	0.22	0.11
Bismuth, Bi	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cadmium, Cd	<0.01	0.02	0.03	0.02	<0.01	<0.01
Cerium, Ce	0.01	0.10	0.02	0.03	0.01	0.02
Cobalt, Co	0.08	1.24	0.07	0.08	0.06	0.11
Copper, Cu	1.87	15.57	1.90	1.59	1.34	2.38
Lead, Pb	0.22	4.08	0.41	0.34	0.22	0.42
Mercury, Hg	1.31	0.24	0.22	0.23	0.15	0.24
Molybdenum, Mo	0.25	0.34	0.18	0.19	0.12	0.13
Nickel, Ni	0.31	1.38	0.44	0.35	0.18	0.62
Selenium, Se	1.46	1.67	0.95	0.84	0.53	0.95
Silver, Ag	0.01	0.02	0.01	0.01	<0.01	0.01
Tantalum, Ta	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Tellurium, Te	<0.01	0.02	0.01	<0.01	0.01	<0.01
Thallium, Tl	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
Thorium, Th	0.01	0.01	<0.01	0.01	<0.01	<0.01
Uranium, U	0.37	0.28	0.21	0.67	0.26	0.64
Zinc, Zn	0.73	11.32	0.73	4.15	1.64	0.84

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

Table 3.1(cont.) **Hydrochemical characteristics of the groundwaters in the CID**

Hydrochemical characteristics	YJ-DD145	YM119	YM118
Date	1/05/98	11/02/98	11/02/98
General characteristics			
pH			
EC (Lab)(ms/m)	46	-	-
pH (Lab)	7.1	-	-
Salinity	-	-	-
TDS	300	550	180
TSS	-	30	340
Oil and Grease	-	-	-
Major ions (mg/L)			
Sodium, Na	60.0	48.0	18.0
Potassium, K	7.4	11.0	4.9
Magnesium, Mg	15.0	54.0	9.0
Calcium, Ca	10.0	59.0	27.0
Iron(II), Fe	-	-	-
Iron(III), Fe	-	-	-
Manganese, Mn	-	-	-
Strontium, Sr	-	-	-
Fluoride, F	-	-	-
Chloride, Cl	75	60	20
Sulphate, SO_4	17	48	15
Bicarbonate, HCO_3	120	410	130
Carbonate, CO_3	<1	<5	<1
Neutral species			
Total silicon (as SiO_2)	-	-	-
Nutrients			
Nitrogen (total)	-	6.8	3.4
Nitrate (as N)	-	-	-
Trace elements (ug/L)			
Aluminium, Al	-	-	-
Antimony, Sb	-	-	-
Arsenic, As	-	-	-
Barium, Ba	-	-	-
Beryllium, Be	-	-	-
Bismuth, Bi	-	-	-
Cadmium, Cd	-	-	-
Cerium, Ce	-	-	-
Cobalt, Co	-	-	-
Copper, Cu	-	-	-
Lead, Pb	-	-	-
Mercury, Hg	-	-	-
Molybdenum, Mo	-	-	-
Nickel, Ni	-	-	-
Selenium, Se	-	-	-
Silver, Ag	-	-	-
Tantalum, Ta	-	-	-
Tellurium, Te	-	-	-
Thallium, Tl	-	-	-
Thorium, Th	-	-	-
Uranium, U	-	-	-
Zinc, Zn	-	-	-

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

Table 3.2 **Hydrochemical characteristics of the surface waters at Yandi**

Hydrochemical characteristics	Discharge	Campsite	Upstream
Date	4/05/98	4/05/98	4/05/98
General characteristics			
pH			
EC (Lab)(ms/m)	-	-	-
pH (Lab)	7.36	7.31	7.36
Salinity	-	-	-
TDS	520	560	600
TSS	16000	20000	6100
Oil and Grease	<5	<5	<5
Major ions (mg/L)			
Sodium, Na	77.0	100	100
Potassium, K	8.0	7.8	7.3
Magnesium, Mg	42.0	42.0	44.0
Calcium, Ca	53.0	56.0	48.0
Iron(II), Fe	-	-	-
Iron(III), Fe	-	-	-
Manganese, Mn	-	-	-
Strontium, Sr	-	-	-
Fluoride, F	-	-	-
Chloride, Cl	120	150	170
Sulphate, SO_4	47	53	58
Bicarbonate, HCO_3	290	290	300
Carbonate, CO_3	<1	<1	<1
Neutral species			
Total silicon (as SiO_2)	-	-	-
Nutrients			
Nitrogen (total)	0.1	0.2	0.2
Nitrate (as N)	-	-	-
Trace elements (ug/L)			
Aluminium, Al	-	-	-
Antimony, Sb	-	-	-
Arsenic, As	-	-	-
Barium, Ba	-	-	-
Beryllium, Be	-	-	-
Bismuth, Bi	-	-	-
Cadmium, Cd	<1	<1	<1
Cerium, Ce	-	-	-
Cobalt, Co	-	-	-
Copper, Cu	<50	<50	<50
Lead, Pb	<5	<5	<5
Mercury, Hg	-	-	-
Molybdenum, Mo	-	-	-
Nickel, Ni	-	-	-
Selenium, Se	-	-	-
Silver, Ag	-	-	-
Tantalum, Ta	-	-	-
Tellurium, Te	-	-	-
Thallium, Tl	-	-	-
Thorium, Th	-	-	-
Uranium, U	-	-	-
Zinc, Zn	<50	<50	<50

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

Table 3.2(cont.) **Hydrochemical characteristics of the surface waters at Yandi**

Hydrochemical characteristics	Marillana1	Marillana2	Marillana3	Marillana4	Marillana5	Marillana6
Date	4/05/98	4/05/98	4/05/98	4/05/98	4/05/98	4/05/98
General characteristics						
pH	-	-	-	-	-	-
EC (Lab)(ms/m)	-	-	-	-	-	-
pH (Lab)	7.8	7.62	7.63	7.16	7.59	7.35
Salinity	-	-	-	-	-	-
TDS	560	550	670	730	740	480
TSS	9700	20000	66	310	2000	2200
Oil and Grease	<5	<5	<5	<5	<5	<5
Major ions (mg/L)						
Sodium, Na	90.0	97.0	120	100	90.0	73.0
Potassium, K	7.7	7.7	12.0	9.3	8.1	7.8
Magnesium, Mg	42.0	44.0	50.0	59.0	46.0	35.0
Calcium, Ca	48.0	48.0	49.0	66.0	57.0	47.0
Iron(II), Fe	-	-	-	-	-	-
Iron(III), Fe	-	-	-	-	-	-
Manganese, Mn	-	-	-	-	-	-
Strontium, Sr	-	-	-	-	-	-
Fluoride, F	-	-	-	-	-	-
Chloride, Cl	130	150	190	260	170	100
Sulphate, SO_4	42	49	55	50	52	44
Bicarbonate, HCO_3	320	310	310	360	260	270
Carbonate, CO_3	<1	<1	<1	<1	<1	<1
Neutral species						
Total silicon (as SiO_2)	-	-	-	-	-	-
Nutrients						
Nitrogen (total)	0.3	1.3	0.3	0.4	0.1	0.1
Nitrate (as N)						
Trace elements (ug/L)						
Aluminium, Al	-	-	-	-	-	-
Antimony, Sb	-	-	-	-	-	-
Arsenic, As	-	-	-	-	-	-
Barium, Ba	-	-	-	-	-	-
Beryllium, Be	-	-	-	-	-	-
Bismuth, Bi	-	-	-	-	-	-
Cadmium, Cd	<1	<1	<1	<1	<1	<1
Cerium, Ce	-	-	-	-	-	-
Cobalt, Co	-	-	-	-	-	-
Copper, Cu	<50	<50	<50	<50	<50	<50
Lead, Pb	<5	<5	<5	<5	<5	<5
Mercury, Hg	-	-	-	-	-	-
Molybdenum, Mo	-	-	-	-	-	-
Nickel, Ni	-	-	-	-	-	-
Selenium, Se	-	-	-	-	-	-
Silver, Ag	-	-	-	-	-	-
Tantalum, Ta	-	-	-	-	-	-
Tellurium, Te	-	-	-	-	-	-
Thallium, Tl	-	-	-	-	-	-
Thorium, Th	-	-	-	-	-	-
Uranium, U	-	-	-	-	-	-
Zinc, Zn	<50	<50	<50	<50	<50	<50

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

Table 3.3 **Hydrochemical characteristics of the basement groundwaters**

Hydrochemical characteristics	Plant	Rail loop	Rail loop	Fauna
Date	1/05/98	1/05/98	11/05/98	11/05/98
General characteristics				
pH	-	-	-	-
EC (Lab)(ms/m)	72	100	-	-
pH (Lab)	7.6	7.1	-	-
Salinity	-	-	-	-
TDS	460	640	700	570
TSS	-	-	3300	9
Oil and Grease	-	-	-	-
Major ions (mg/L)				
Sodium, Na	71.0	76.0	110	58.0
Potassium, K	7.0	13.0	11.0	11.0
Magnesium, Mg	32.0	61.0	51.0	68.0
Calcium, Ca	36.0	70.0	78.0	56.0
Iron(II), Fe	-	-	-	-
Iron(III), Fe	-	-	-	-
Manganese, Mn	-	-	-	-
Strontium, Sr	-	-	-	-
Fluoride, F	-	-	-	-
Chloride, Cl	90	95	120	96
Sulphate, SO_4	39	49	66	52
Bicarbonate, HCO_3	270	480	480	430
Carbonate, CO_3	<1	<1	<1	<1
Neutral species				
Total silicon (as SiO_2)	-	-	-	-
Nutrients				
Nitrogen (total)	-	-	4.0	0.9
Nitrate (as N)	-	-	-	-
Trace elements (ug/L)				
Aluminium, Al				
Antimony, Sb	-	-	-	-
Arsenic, As	-	-	-	-
Barium, Ba	-	-	-	-
Beryllium, Be	-	-	-	-
Bismuth, Bi	-	-	-	-
Cadmium, Cd	-	-	-	-
Cerium, Ce	-	-	-	-
Cobalt, Co	-	-	-	-
Copper, Cu	-	-	-	-
Lead, Pb	-	-	-	-
Mercury, Hg	-	-	-	-
Molybdenum, Mo	-	-	-	-
Nickel, Ni	-	-	-	-
Selenium, Se	-	-	-	-
Silver, Ag	-	-	-	-
Tantalum, Ta	-	-	-	-
Tellurium, Te	-	-	-	-
Thallium, Tl	-	-	-	-
Thorium, Th	-	-	-	-
Uranium, U	-	-	-	-
Zinc, Zn	-	-	-	-

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

Table 3.4 **Summary of water quality checks**

Sample	Ionic balance	Difference between measured and calculated Electrical conductivity	Difference between measured and calculated TDS
PU06	5.1%	-	0.3%
GS53	-0.7%	-	13.2%
GS8	-1.9%	-	14.5%
YC218	-	-	-
YC216	-	-	-
YC217	-	-	-
YC215	-	-	-
DW1	-1.6%	9.5%	-
YC214	-	-	-
YC213	-	-	-
YC207	-	-	-
DW2	-0.2%	6.6%	3.0%
YC205	-	-	-
YC147	-	-	-
YM104	3.1%	-	-9.5%
YM114	3.6%	-	2.3%
YM118	3.6%	-	1.2%
YM118	-0.7%	-	9.7%
YM119	0.9%	-	10.2%

Note - no value

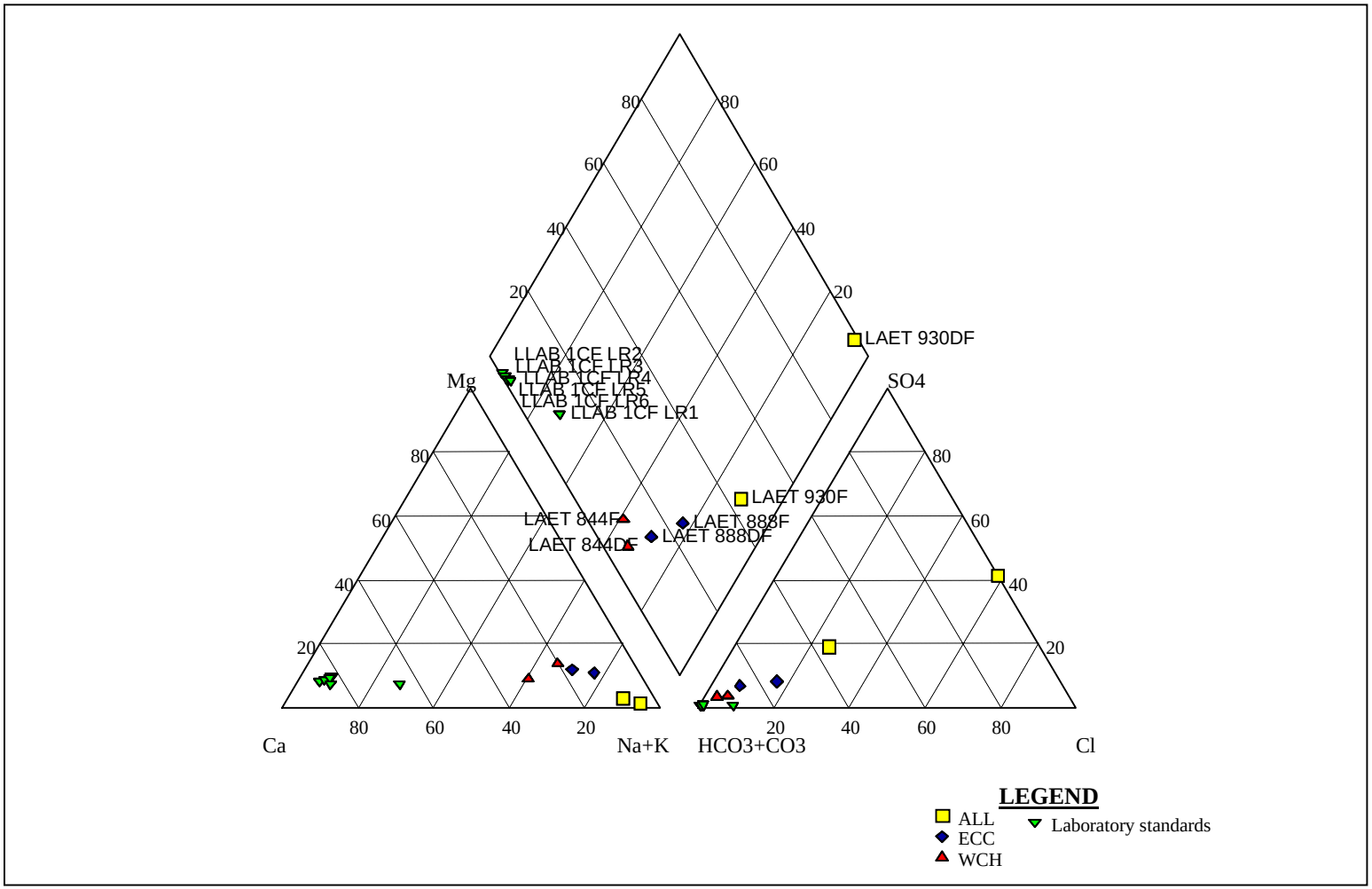


Figure 3.1

DISTRIBUTION OF MAJOR IONS - QUALITY CONTROL SAMPLES

3.4 ROCK SAMPLES

The CID was sampled at a 50m grid spacing using percussion and rotary drilling methods. During the drilling the bores were logged and samples were collected for analysis. The borehole cores and rock chippings were then put in storage by Hamersley Iron.

A selection of overburden material rock samples from three sections were collected from the storage. The rock types chosen were alluvium, eastern clay conglomerate (ECC) and weathered channel horizon (WCH). These three rock types make up the majority of the overburden. The sample depth and rock types of the samples are shown in Table 3.4.

Three regional rock samples were collected and analysed. The rock types were dolerite, BIF and a shale. The results are shown in Table 3.8.

Table 3.5 **Samples chosen for further analysis**

Bore hole	Alluvium	Eastern clay conglomerate	Western channel horizon
Section 13.95			
YJ-P184	-	0-2m (AET 827)	2-4m (AET 828)
YJ-P185	-	0-2m (AET 837)	6-8.2m (AET 840)
YJ-P186	-	0-2m (AET 841)	6-8m (AET 844)
YJ-P187	0-2m (AET 851)	4-6m (AET 853)	10-12m (AET 856)
YJ-P188	0-2m (AET 861)	8-10m (AET 865)	-
Section 14.45			
YJ-P190	-	-	0-2m (AET 878)
YJ-P191	-	0-2m (AET 888)	4-6m (AET 890)
YJ-P192	-	0-2m (AET 898)	-
YJ-P193	-	0-2m (AET 908)	4-6m (AET 910)
YJ-P194	0-2m (AET 918)	4-6.2m (AET 920)	-
Section 15.00			
YJ-P196	0-2m (AET 930)	-	-
YJ-P197	-	0-2m (AET 932)	2-4m (AET 933)
YJ-P198	0-2m (AET 939)	-	2-4m (AET 940)

The geochemical characteristics determined for the rock samples by Hamersley Iron and the School of Applied Chemistry at Curtin University of Technology are listed below.

3.4.1 COMMON ELEMENTS, OXIDES AND CHARACTERISTICS

Aluminium oxide, calcium oxide, iron, magnesium oxide, manganese, phosphorus, silicon dioxide, sulphur, titanium dioxide and total loss on ignition (LOI).

3.4.2 TRACE ELEMENTS

Antimony, arsenic, barium, beryllium, bismuth, cadmium, cerium, chromium, copper, lead, mercury, molybdenum, nickel, selenium, silver, strontium, tellurium, thallium, thorium, uranium, and zinc.

3.5 TOTAL DIGEST ROCK RESULTS

Twenty-five samples of overburden material were taken from three cross sections (shown in Figure 2.2) of the ore body. The samples are listed by rock type alluvium, eastern clay conglomerate and western channel horizon.

Table 3.6 **Chemical characteristics of the alluvium rock samples**

Chemical characteristics	AET 851	AET 861	AET 918	AET 930	AET 930D	AET 939
Major Constituents						
Aluminium, as Al_2O_3	109800	122500	82800	109700	-	123000
Magnesium, as MgO	1500	800	1000	1900	-	2600
Calcium, CaO*	900	700	2800	700	-	5100
Iron, Fe	426800	400200	436300	250100	-	296500
Manganese, as Mn	200	300	300	300	-	200
Phosphorus, P	270	230	360	260	-	210
Sulphur, S	120	180	130	170	-	170
Silica, as SiO_2	211600	236100	231900	457100	-	370100
Titanium, Ti	5433	4709	3878	3764	3643	3779
Trace elements						
Antimony, Sb	9.78	9.32	8.85	3.39	3.35	3.36
Arsenic, As	17.1	18.0	16.3	6.76	6.48	7.71
Barium, Ba	81	60	110	135	129	102
Beryllium, Be	1.37	1.32	2.73	1.88	1.86	2.16
Bismuth, Bi	0.728	0.739	0.451	0.335	0.335	0.244
Cadmium, Cd	0.158	0.137	0.117	0.0406	0.0496	0.0541
Cerium, Ce	36.7	24.5	46.7	42.5	40.6	37.2
Chromium, Cr	177	105	156	128	131	117
Copper, Cu	65.2	58.8	61.9	34.5	34.9	36.7
Lead, Pb	66.0	69.3	67.4	28.7	28.5	29.7
Molybdenum, Mo	7.46	6.62	3.78	2.58	2.43	3.33
Nickel, Ni	33.3	21.0	23.5	30.3	29.9	30.7
Selenium, Se	1.24	0.71	0.54	<0.01	<0.01	<0.01
Silver, Ag	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium, Sr	17.9	10.5	15.5	16.5	16.1	13.8
Tellurium, Te	0.187	0.160	0.155	0.0733	0.0955	0.0673
Thallium, Tl	0.255	0.172	0.164	0.539	0.522	0.351
Thorium, Th	26.3	25.0	18.9	13.2	12.6	11.7
Uranium, U	4.07	4.77	2.50	1.89	1.90	2.34
Zinc, Zn	39.0	38.8	99.5	35.2	36.4	26.4

Note all values are mg/kg, - not measured.

Table 3.7 **Chemical characteristics of the eastern clay conglomerate rock samples**

Chemical characteristics	AET 827	AET 837	AET 841	AET 853	AET 865
Major Constituents					
Aluminium, as Al_2O_3	103000	100800	136500	127500	169700
Magnesium, as MgO	2300	1500	3800	11800	2800
Calcium, CaO*	1200	500	18200	4400	1400
Iron, Fe	456300	451300	325200	228800	346200
Manganese, as Mn	400	200	200	200	100
Phosphorus, P	270	170	140	140	180
Sulphur, S	270	140	280	260	170
Silica, as SiO_2	104600	140400	259700	410100	238900
Titanium, Ti	5455	4767	5482	4845	6075
Trace elements					
Antimony, Sb	2.42	2.90	4.47	4.72	7.30
Arsenic, As	9.72	17.2	15.5	8.63	17.5
Barium, Ba	159	62	783	108	61
Beryllium, Be	1.14	1.18	1.34	0.90	0.98
Bismuth, Bi	0.284	0.189	0.331	0.465	0.364
Cadmium, Cd	0.127	0.102	0.112	0.105	0.216
Cerium, Ce	46.8	33.1	56.5	27.6	23.0
Chromium, Cr	42.7	76.7	113	71.3	49.5
Copper, Cu	32.3	45.3	63.5	51.0	38.4
Lead, Pb	21.1	22.6	51.0	41.3	43.0
Molybdenum, Mo	6.08	5.58	6.06	3.62	5.17
Nickel, Ni	26.2	41.4	43.8	22.1	16.6
Selenium, Se	1.08	0.68	0.97	0.20	0.44
Silver, Ag	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium, Sr	16.3	9.8	36.6	40.9	21.2
Tellurium, Te	0.0576	0.0666	0.109	0.0523	0.0961
Thallium, Tl	0.0793	0.153	0.258	0.196	0.0412
Thorium, Th	11.0	10.7	17.4	18.0	33.3
Uranium, U	3.13	3.57	4.29	2.79	4.24
Zinc, Zn	29.1	14.0	26.5	41.6	31.7

Note all values are mg/kg, - not measured.

Table 3.7(cont.) **Chemical characteristics of the Eastern clay conglomerate rock samples**

Chemical characteristics	AET 888	AET 888D	AET 898	AET 908	AET 920	AET 932
Major Constituents						
Aluminium, as Al_2O_3	151200	-	83500	115200	159200	88800
Magnesium, as MgO	1700	-	1800	2000	4100	1600
Calcium, CaO*	800	-	1600	2500	1900	700
Iron, Fe	368900	-	450900	394600	325400	455400
Manganese, as Mn	200	-	200	200	200	300
Phosphorus, P	130	-	190	200	100	540
Sulphur, S	140	-	420	150	170	170
Silica, as SiO_2	197300	-	153600	212900	259100	171300
Titanium, Ti	8020	7869	4812	5718	5504	3562
Trace elements						
Antimony, Sb	4.48	4.45	2.19	3.58	3.68	7.92
Arsenic, As	17.1	17.5	16.0	13.8	13.3	18.1
Barium, Ba	52	52	1292	163	261	57
Beryllium, Be	2.11	2.24	2.31	2.29	3.07	3.00
Bismuth, Bi	0.267	0.273	0.103	0.226	0.222	0.439
Cadmium, Cd	0.163	0.144	0.0757	0.0987	0.0758	0.0966
Cerium, Ce	28.6	28.6	23.5	24.6	29.1	33.0
Chromium, Cr	76.4	77.1	57.0	101	69.7	110
Copper, Cu	50.7	49.5	39.9	42.5	61.8	66.7
Gallium, Ga	36.2	36.5	36.6	24.2	28.6	19.1
Lead, Pb	36.2	35.7	15.8	27.2	42.9	45.3
Molybdenum, Mo	6.72	6.91	3.61	4.02	4.42	4.40
Nickel, Ni	48.1	49.1	46.7	38.3	44.3	31.7
Selenium, Se	0.77	0.93	0.87	<0.01	<0.01	0.80
Silver, Ag	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium, Sr	12.0	12.0	17.3	23.8	31.4	10.0
Tellurium, Te	0.0941	0.0756	0.0592	0.0554	0.0862	0.111
Thallium, Tl	0.139	0.124	0.148	0.160	0.108	0.262
Thorium, Th	19.3	19.1	8.3	14.6	12.3	14.9
Uranium, U	4.82	4.91	2.80	3.56	3.63	3.82
Zinc, Zn	16.5	15.6	12.4	20.1	12.5	103.3

Note all values are mg/kg, - not measured.

Table 3.8 **Chemical characteristics of the weathered channel horizon rock samples**

Chemical characteristics	AET 828	AET 840	AET 844	AET 844D	AET 856	AET 878
Major Constituents						
Aluminium, as Al_2O_3	32200	82700	45800	-	42400	68200
Magnesium, as MgO	1100	5600	900	-	1700	1300
Calcium, CaO*	500	11700	1300	-	1000	2500
Iron, Fe	559400	422300	548700	-	541600	529700
Manganese, as Mn	300	200	300	-	200	300
Phosphorus, P	370	300	390	-	370	310
Sulphur, S	200	140	90	-	80	140
Silica, as SiO_2	71500	183900	81190	-	86300	89100
Titanium, Ti	2735	4704	3293	3046	2954	4621
Trace elements						
Antimony, Sb	0.94	1.07	1.16	1.00	1.02	1.63
Arsenic, As	12.3	11.5	13.3	12.7	14.9	11.1
Barium, Ba	39	34	47	46	31	301
Beryllium, Be	1.14	1.04	1.41	1.53	1.80	2.35
Bismuth, Bi	0.086	0.139	0.096	0.093	0.082	0.149
Cadmium, Cd	0.052	0.0810	0.0574	0.0330	0.0431	0.0748
Cerium, Ce	22.2	22.7	27.1	25.3	17.7	29.8
Chromium, Cr	24.6	35.1	33.3	30.4	30.0	38.6
Copper, Cu	14.2	24.5	21.3	19.1	19.7	30.6
Lead, Pb	7.8	9.7	10.5	9.6	12.5	16.1
Molybdenum, Mo	4.24	3.30	4.45	3.99	4.09	4.36
Nickel, Ni	12.0	15.1	18.8	17.4	11.4	28.2
Selenium, Se	0.76	0.34	0.32	0.32	0.50	1.12
Silver, Ag	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium, Sr	9.2	37.1	19.1	18.2	17.8	31.7
Tellurium, Te	0.0169	0.0389	0.0428	0.0370	0.0245	0.0338
Thallium, Tl	0.0913	0.0699	0.0943	0.0799	0.0656	0.230
Thorium, Th	4.2	8.8	4.0	3.7	4.3	8.5
Uranium, U	2.05	2.24	1.58	1.74	1.71	2.54
Zinc, Zn	22.8	16.0	10.9	14.5	12.6	15.2

Note all values are mg/kg, - not measured.

Table 3.8(cont.) **Chemical characteristics of the weathered channel horizon rock samples**

Chemical characteristics	AET 890	AET 900	AET 910	AET 933	AET 940
Major Constituents					
Aluminium, as Al_2O_3	49500	72600	84400	153300	103100
Magnesium, as MgO	2500	1600	1900	1800	1400
Calcium, CaO*	1100	900	800	600	800
Iron, Fe	532300	515100	519200	381200	482500
Manganese, as Mn	500	300	300	300	200
Phosphorus, P	410	360	310	350	270
Sulphur, S	70	80	100	200	110
Silica, as SiO_2	101100	107200	88600	194100	114800
Titanium, Ti	3308	4446	5055	5453	4886
Trace elements					
Antimony, Sb	1.04	3.35	2.03	3.72	2.21
Arsenic, As	12.0	12.6	10.7	10.3	10.7
Barium, Ba	123	94	23	44	53
Beryllium, Be	2.27	1.75	1.73	2.39	1.95
Bismuth, Bi	0.082	0.167	0.139	0.218	0.119
Cadmium, Cd	0.0618	0.0650	0.0821	0.145	0.0758
Cerium, Ce	23.5	21.5	26.7	27.5	27.2
Chromium, Cr	29.1	73.2	51.6	63.0	63.3
Copper, Cu	15.9	21.2	26.4	28.2	29.1
Lead, Pb	9.0	15.0	19.8	31.6	24.5
Molybdenum, Mo	3.84	4.99	4.76	3.68	4.75
Nickel, Ni	17.1	18.5	21.4	32.5	28.8
Selenium, Se	0.49	0.37	0.08	0.11	0.39
Silver, Ag	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium, Sr	13.6	12.9	10.2	7.9	8.2
Tellurium, Te	0.0222	0.0802	0.0517	0.0445	0.0427
Thallium, Tl	0.0793	0.0915	0.0626	0.153	0.0745
Thorium, Th	4.8	7.9	7.9	19.0	9.0
Uranium, U	1.39	1.85	2.36	3.68	2.59
Zinc, Zn	9.9	8.6	7.6	33.4	11.1

Note all values are mg/kg, - not measured.

Table 3.9 **Chemical characteristics of the regional rock samples**

Chemical characteristics	Calcite mineralized Shale	Shale	BIF	Dolerite
Major Constituents				
Aluminium, as Al_2O_3	21400	103500	139800	12200
Magnesium, as MgO	11300	111500	72800	1600
Calcium, CaO*	325600	24700	80600	23200
Iron, Fe	82768	177750	190409	59316
Manganese, as Mn	315	711	219	1240
Phosphorus, P	600	1100	700	700
Sulphur, S	-	-	-	-
Silica, as SiO_2	205200	317200	503000	517700
Titanium, Ti	1131	4697	173	2944
Trace elements				
Antimony, Sb	0.82	0.39	0.65	2.00
Arsenic, As	4.2	1.5	0.8	1.5
Barium, Ba	26	90	37	292
Beryllium, Be	0.43	1.24	1.01	0.56
Bismuth, Bi	0.05	0.05	0.35	0.02
Cadmium, Cd	0.08	0.06	0.02	0.08
Chromium, Cr	12.5	50.0	3.1	79.0
Copper, Cu	29.4	16.3	51.4	80.0
Lead, Pb	5.5	4.1	63.3	16.6
Molybdenum, Mo	0.16	0.08	0.13	0.28
Nickel, Ni	14.6	36.0	5.0	69.9
Selenium, Se	<0.01	<0.01	<0.01	<0.01
Silver, Ag	0.07	0.06	0.04	0.06
Strontium, Sr	37.9	71.9	65.3	129.0
Tellurium, Te	0.06	0.13	0.06	0.11
Thallium, Tl	0.05	0.12	0.05	0.32
Thorium, Th	2.9	6.7	1.0	3.4
Uranium, U	0.47	1.04	0.37	0.77
Zinc, Zn	43.4	187.1	60.7	93.4

Note all values are mg/kg, - not measured.

Table 3.10 **Quality control – Acid washed quartz samples**

Hydrochemical characteristic	Quartz1	Quartz2	Quartz3	Quartz4
Sodium, Na	103	105	19	18
Potassium, K	40	24	14	15
Magnesium, Mg	75	30	15	14
Calcium, Ca	282	96	55	47
Iron, Fe	233	183	125	146
Manganese, Mn	0.90	0.94	0.37	0.36
Strontium, Sr	1.96	2.48	4.06	5.17
Trace elements				
Antimony, Sb	<0.00001	0.00002	<0.00001	0.00001
Arsenic, As	<0.00001	<0.00001	0.00001	0.00007
Barium, Ba	0.00184	0.00127	0.00170	0.00195
Beryllium, Be	<0.00001	<0.00001	0.00002	0.00002
Bismuth, Bi	<0.00001	<0.00001	<0.00001	<0.00001
Cadmium, Cd	<0.00001	<0.00001	0.00001	<0.00001
Chromium, Cr	<0.00001	<0.00001	<0.00001	<0.00001
Cobalt, Co	0.07142	0.07522	0.02191	0.02200
Copper, Cu	0.00063	0.00069	0.00051	0.00043
Lead, Pb	0.00120	0.0212	0.00059	0.00041
Molybdenum, Mo	0.00006	0.00007	0.00012	0.00011
Nickel, Ni	0.00019	0.00018	0.00007	<0.00001
Selenium, Se	<0.00001	<0.00001	<0.00001	<0.00001
Silver, Ag	0.00002	0.00005	0.00002	<0.00001
Tellurium, Te	<0.00001	<0.00001	<0.00001	<0.00001
Thallium, Tl	0.00004	0.00004	0.00003	0.00002
Thorium, Th	0.00001	0.00002	0.00034	0.00036
Uranium, U	0.00003	0.00002	0.00010	0.00014
Zinc, Zn	<0.00001	<0.00001	<0.00001	<0.00001

Note all values are mg/kg, - not measured.

3.6 LEACHATE ANALYSIS

The hydrochemical characteristics analysed for leachate samples are listed below.

3.6.1 GENERAL CHARACTERISTIC

Electrical Conductivity (EC), pH, Total Dissolved Solids (TDS) or salinity (by equivalent EC) and alkalinity (as $CaCO_3$).

3.6.2 MAJOR AND MINOR ANIONS

Bromide, chloride, fluoride, sulphate and hydroxide, bicarbonate and carbonate by calculation.

3.6.3 MAJOR CATIONS

Calcium, iron, magnesium, manganese, potassium sodium and strontium.

3.6.4 NEUTRAL SPECIES

Total silicon.

3.6.5 NUTRIENTS

Nitrate and phosphate.

3.6.6 TRACE ELEMENTS

Antimony, arsenic, barium, beryllium, bismuth, cadmium, cerium, chromium, cobalt, copper, lead, molybdenum, nickel, selenium, silver, tellurium, thallium, thorium, uranium and zinc.

3.7 LEACHATE RESULTS FOR FINE GRAINED SAMPLES USING WATER

This extraction simulates the equilibrium reached by the rainwater and the crushed rock samples. The results of the leachate tests are shown in Tables 3.11 - 3.13. The samples were grouped by rock types; alluvium, eastern clay conglomerate and western channel horizon.

Table 3.11 **Hydrochemical characteristics of the alluvium leachate samples**

Hydrochemical characteristic	LAET 851F	LAET 861F	LAET 918F	LAET 930F	LAET 930DF	LAET 939F
pH	6.7	6.4	7.9	6.5	5.3	7.4
EC (uS/cm)	15.0	20.6	87.5	12.0	14.3	14.7
TDS (at180 °C)	-	-	-	-	-	-
Alkalinity (as $CaCO_3$)	35	138	1773	43	0	58
Major ions						
Sodium, Na	21	41	10	23	37	23
Potassium, K	18	14	27	14	6.4	24
Magnesium, Mg	1.4	2.0	26	0.5	0.3	0.2
Calcium, Ca	4.9	8.7	617	2.6	1.4	0.3
Iron, Fe	<0.0002	0.4	<0.0002	1.1	0.5	8.2
Manganese, Mn	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Strontium, Sr	0.0907	0.1559	1.2488	0.0434	0.0362	0.0978
Bromide, Br	<1	<1	<1	<1	<1	<1
Fluoride, F	19.2	3.0	4.1	2.9	3.9	1.9
Chloride, Cl	20.2	27.3	7.2	13.6	18.9	5.8
Sulphate, SO_4	18.7	30.5	19.1	14.0	17.8	11.8
Bicarbonate, HCO_3	42	169	2146	52	0.0	70
Carbonate, CO_3	0.0	0.0	9.7	0.0	0.0	0.1
Hydroxide, OH	0.0	0.0	0.3	0.0	0.0	0.1
Nutrients						
Nitrate (as NO_3)	1.0	3.1	4.0	4.1	1.9	2.6
Phosphate (PO_4)	<1	<1	<1	<1	<1	<1
Trace elements						
Antimony, Sb	0.0006	0.0007	0.0014	0.0004	0.0003	0.0005
Arsenic, As	0.0033	0.0033	0.0136	0.0033	0.0034	0.0050
Barium, Ba	0.2	1.5	1.4	0.2	0.3	1.3
Beryllium, Be	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Bismuth, Bi	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Cadmium, Cd	0.0014	0.0006	0.0003	0.0003	0.0008	0.0004
Chromium, Cr	0.0268	0.0333	0.0299	0.0242	0.0243	0.0477
Cobalt, Co	0.0035	0.0042	0.0039	0.0222	0.0179	0.0241
Copper, Cu	0.0057	0.0101	0.0100	0.0026	0.0143	0.0090
Lead, Pb	0.0039	0.0047	0.0033	0.0044	0.0066	0.0108
Molybdenum, Mo	0.0039	0.0019	0.0204	0.0016	0.0023	0.0016
Nickel, Ni	0.0223	0.0135	0.0221	0.0149	0.0249	0.0305
Selenium, Se	0.0255	0.0314	0.0385	0.0232	0.0258	0.0266
Silver, Ag	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Tellurium, Te	0.0004	0.0003	0.0004	0.0003	0.0004	0.0005
Thallium, Tl	0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Thorium, Th	0.0003	0.0005	0.0002	0.0004	0.0003	0.0006
Uranium, U	<0.0002	0.0002	0.0010	<0.0002	<0.0002	0.0008
Zinc, Zn	0.1392	0.9623	0.1317	0.2557	0.2769	0.9280

Note all values are mg/kg), pH is dimensionless, - not measured.

Table 3.12 **Hydrochemical characteristics of the eastern clay conglomerate leachate samples**

Hydrochemical characteristic	LAET 827F	LAET 837F	LAET 841F	LAET 853F	LAET 865F
pH	6.3	6.5	7.8	8.1	6.8
EC (uS/cm)	90.9	59.4	94.5	108.5	22.6
TDS (at180 °C)	-	-	-	-	-
Alkalinity (as $CaCO_3$)	220	68	1689	1199	186
Major ions					
Sodium, Na	137	144	127	140	80
Potassium, K	24	47	60	45	6.0
Magnesium, Mg	15	6.1	23	28	<0.2
Calcium, Ca	53	14	821	24	0.9
Iron, Fe	0.85	0.2	<0.0002	1.2	<0.0002
Manganese, Mn	0.0007	<0.0002	<0.0002	<0.0002	<0.0002
Strontium, Sr	0.6303	0.3080	1.7848	0.5059	0.0218
Bromide, Br	<1	<1	<1	<1	<1
Fluoride, F	12.3	3.0	8.1	19.1	10.9
Chloride, Cl	209.5	199.1	196.3	20.2	37.4
Sulphate, SO_4	72.9	34.3	92.3	18.6	8.7
Bicarbonate, HCO_3	269	83	2048	1442	227
Carbonate, CO_3	0.0	0.0	7.2	11.0	0.1
Hydroxide, OH	0.0	0.0	0.2	0.5	0.0
Nutrients		0			
Nitrate (as NO_3)	4.1	2.7	3.0	0.0	0.7
Phosphate (PO_4)	<1	<1	<1	<1	<1
Trace elements		0			
Antimony, Sb	0.0012	0.0015	0.0009	0.0009	0.0008
Arsenic, As	0.0042	0.0094	0.0153	0.0229	0.0078
Barium, Ba	3.1	0.2	8.2	1.9	0.1
Beryllium, Be	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Bismuth, Bi	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Cadmium, Cd	0.0030	0.0194	0.0017	0.0005	0.0006
Cerium, Ce	0.0026	0.0126	0.0009	0.0011	0.0004
Chromium, Cr	0.0284	0.0377	0.0367	0.0272	0.0268
Cobalt, Co	0.0440	0.0149	0.0060	0.0040	0.0024
Copper, Cu	0.0094	0.0847	0.0187	0.0085	0.0050
Lead, Pb	0.0203	0.0418	0.0071	0.0023	0.0039
Molybdenum, Mo	0.0046	0.0033	0.0185	0.0223	0.0035
Nickel, Ni	0.0288	0.5025	0.0254	0.0116	0.0161
Selenium, Se	0.0309	0.0268	0.0312	0.0246	0.0293
Silver, Ag	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Tellurium, Te	0.0006	0.0003	0.0004	0.0005	0.0005
Thallium, Tl	<0.0002	0.0005	0.0006	0.0002	<0.0002
Thorium, Th	0.0003	<0.0002	0.0002	0.0006	0.0005
Uranium, U	0.0003	0.0004	0.0015	0.0002	<0.0002
Zinc, Zn	0.4762	3.8424	0.2041	0.1667	0.1963

Note all values are mg/kg, pH is dimensionless, - not measured.

Table 3.12(cont.) **Hydrochemical characteristics of the eastern clay conglomerate leachate samples**

Hydrochemical characteristic	LAET 888F	LAET 888DF	LAET 898F	LAET 908F	LAET 920F	LAET 932F
pH	6.9	6.7	7.9	7.7	7.4	6.1
EC (uS/cm)	17.2	14.7	83.3	85.2	36.2	20.6
TDS (at180 °C)	-	-	-	-	-	-
Alkalinity (as $CaCO_3$)	127	162	1032	1345	234	81
Major ions						
Sodium, Na	26	17	23	34	125	28
Potassium, K	14	14	14	29	15	30
Magnesium, Mg	2.5	2.1	29	26	0.3	1.6
Calcium, Ca	4.7	5.3	447	425	3.5	5.3
Iron, Fe	<0.0002	<0.0002	<0.0002	1.1098	0.4577	<0.0002
Manganese, Mn	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Strontium, Sr	0.2021	0.1902	1.5496	2.0592	0.0253	0.0991
Bromide, Br	1.6	<1	<1	<1	<1	<1
Fluoride, F	3.4	3.2	14.0	6.6	6.8	3.0
Chloride, Cl	20.1	10.3	11.4	19.1	29.3	20.4
Sulphate, SO_4	12.9	12.2	178.1	77.3	97.0	49.1
Bicarbonate, HCO_3	154	197	1248	1633	285	99
Carbonate, CO_3	0.1	0.1	6.1	4.5	0.4	0.0
Hydroxide, OH	0.0	0.0	0.3	0.2	0.1	0.0
Nutrients						
Nitrate (as NO3)	1.1	1.0	2.6	42.0	0.0	0.9
Phosphate (PO4)	<1	<1	<1	<1	<1	<1
Trace elements						
Antimony, Sb	0.0007	0.0004	0.0006	0.0007	0.0007	0.0004
Arsenic, As	0.0019	0.0017	0.0045	0.0142	0.0135	0.0016
Barium, Ba	0.9	0.6	9.5	3.6	0.1	0.2
Beryllium, Be	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Bismuth, Bi	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Cadmium, Cd	0.0003	0.0003	0.0006	0.0004	<0.0002	0.0008
Cerium, Ce	0.0005	0.0005	0.0008	0.0018	0.0011	0.0009
Chromium, Cr	0.0221	0.0207	0.0195	0.0285	0.0241	0.0172
Cobalt, Co	0.0016	0.0013	0.0027	0.0026	0.0018	0.0036
Copper, Cu	0.0105	0.0039	0.0035	0.0116	0.0119	0.0131
Lead, Pb	0.0034	0.0039	0.0025	0.0035	0.0036	0.0039
Molybdenum, Mo	0.0043	0.0028	0.0121	0.0352	0.0063	0.0012
Nickel, Ni	0.0127	0.0091	0.0136	0.0175	0.0254	0.0170
Selenium, Se	0.0255	0.0253	0.0426	0.0315	0.0290	0.0254
Silver, Ag	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Tellurium, Te	0.0004	0.0003	0.0005	0.0005	0.0005	0.0005
Thallium, Tl	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Thorium, Th	<0.0002	<0.0002	0.0007	0.0004	0.0003	<0.0002
Uranium, U	<0.0002	<0.0002	<0.0002	0.0013	<0.0002	<0.0002
Zinc, Zn	0.3342	0.2744	1.2456	0.1469	0.1432	0.2153

Note all values are mg/kg, pH is dimensionless, - not measured.

Table 3.13 **Hydrochemical characteristics of the western channel horizon leachate samples**

Hydrochemical characteristic	LAET 828F	LAET 840F	LAET 844F	LAET 844DF	LAET 856F	LAET 878F
pH	6.5	8.3	6.9	7.3	7.4	7.6
EC (uS/cm)	40.6	148.2	41.7	37.6	26.5	91.7
TDS (at180 °C)	-	-	-	-	-	-
Alkalinity (as $CaCO_3$)	0	1937	576	581	290	1539
Major ions						
Sodium, Na	139	335	86	79	99	21
Potassium, K	16	89	26	24	8.4	13
Magnesium, Mg	7.8	42	7.8	10	0.4	22
Calcium, Ca	18	212	44	25	4.0	661
Iron, Fe	1.1533	<0.0002	13.1516	0.2679	4.1790	<0.0002
Manganese, Mn	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Strontium, Sr	0.3607	0.8801	0.3483	0.3860	0.0468	2.2757
Bromide, Br	<1	<1	<1	<1	<1	<1
Fluoride, F	0.0	24.1	9.9	10.4	8.2	12.9
Chloride, Cl	216.5	272.6	27.0	15.3	25.0	13.3
Sulphate, SO_4	61.5	77.6	21.7	19.0	11.8	106.8
Bicarbonate, HCO_3	0.0	2318	702	707	352	1870
Carbonate, CO_3	0.0	25.6	0.3	0.8	0.5	4.6
Hydroxide, OH	0.0	0.7	0.0	0.1	0.1	0.1
Nutrients						
Nitrate (as NO_3)	2.8	1.3	0.9	0.5	0.5	6.8
Phosphate (PO_4)	<1	<1	<1	<1	<1	<1
Trace elements						
Antimony, Sb	0.0005	0.0006	0.0004	0.0004	0.0005	0.0006
Arsenic, As	0.0034	0.0246	0.0054	0.0030	0.0052	0.0054
Barium, Ba	0.6	0.1	1.1	0.9	0.1	5.3
Beryllium, Be	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Bismuth, Bi	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Cadmium, Cd	0.0011	0.0007	0.0005	0.0018	0.0003	0.0003
Cerium, Ce	0.0029	0.0004	0.0034	0.0012	0.0011	0.0006
Chromium, Cr	0.0259	0.0208	0.0320	0.0256	0.0330	0.0257
Cobalt, Co	0.0304	0.0021	0.0370	0.0043	0.0078	0.0023
Copper, Cu	0.0070	0.0068	0.0162	0.0053	0.0091	0.0078
Lead, Pb	0.0079	0.0081	0.0063	0.0037	0.0040	0.0035
Molybdenum, Mo	0.0013	0.0283	0.0095	0.0197	0.0088	0.0256
Nickel, Ni	0.0361	0.0118	0.0329	0.0172	0.0107	0.0196
Selenium, Se	0.0313	0.0305	0.0255	0.0242	0.0233	0.0369
Silver, Ag	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Tellurium, Te	0.0006	0.0005	0.0005	0.0002	0.0003	0.0005
Thallium, Tl	<0.0002	<0.0002	0.000205	<0.0002	<0.0002	<0.0002
Thorium, Th	0.0003	0.0005	0.0006	0.0005	0.0004	0.0004
Uranium, U	<0.0002	0.0003	0.0007	0.0002	0.0002	0.0009
Zinc, Zn	0.1531	0.1321	0.5415	0.1459	0.1130	0.3269

Note all values are mg/kg, pH is dimensionless, - not measured.

Table 3.13(cont.) **Hydrochemical characteristics of the western channel horizon leachate samples**

Hydrochemical characteristic	LAET 890F	LAET 900F	LAET 910F	LAET 933F	LAET 940F
pH	7.7	7.0	7.6	6.4	6.8
EC (uS/cm)	60.6	33.5	27.2	15.7	15.8
TDS (at180 °C)	-	-	-	-	-
Alkalinity (as $CaCO_3$)	69	161	184	69	127
Major ions					
Sodium, Na	41	46	38	26	26
Potassium, K	3.7	10	13	12	17
Magnesium, Mg	3.2	2.4	4.1	1.5	1.3
Calcium, Ca	5.8	3.1	4.7	3.1	1.2
Iron, Fe	11.8248	1.5469	5.9743	<0.0002	2.5168
Manganese, Mn	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Strontium, Sr	0.1722	0.0981	0.2142	0.0866	0.0986
Bromide, Br	<1	<1	<1	<1	<1
Fluoride, F	10.2	5.4	8.0	3.0	5.0
Chloride, Cl	9.1	19.7	12.2	20.9	10.5
Sulphate, SO_4	55.9	22.9	38.8	34.9	13.5
Bicarbonate, HCO_3	84	196	223	84	155
Carbonate, CO_3	0.2	0.1	0.4	0.0	0.1
Hydroxide, OH	0.2	0.0	0.1	0.0	0.0
Nutrients					
Nitrate (as NO_3)	1.9	0.0	2.9	0.7	0.0
Phosphate (PO_4)	<1	<1	<1	<1	<1
Trace elements					
Antimony, Sb	0.0006	0.0005	0.0005	0.0005	0.0005
Arsenic, As	0.0046	0.0022	0.0043	0.0017	0.0015
Barium, Ba	1.3	0.9	1.6	0.8	0.5
Beryllium, Be	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Bismuth, Bi	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Cadmium, Cd	0.0004	0.0005	0.0016	0.0006	0.0003
Cerium, Ce	0.0032	0.0013	0.0069	0.0010	0.0070
Chromium, Cr	0.0283	0.0214	0.0243	0.0199	0.0215
Cobalt, Co	0.0138	0.0037	0.0071	0.0029	0.0045
Copper, Cu	0.0079	0.0047	0.0106	0.0088	0.0076
Lead, Pb	0.0057	0.0030	0.0069	0.0035	0.0042
Molybdenum, Mo	0.0035	0.0028	0.0029	0.0011	0.0013
Nickel, Ni	0.0204	0.0109	0.0249	0.0175	0.0133
Selenium, Se	0.0289	0.0253	0.0222	0.0211	0.0252
Silver, Ag	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Tellurium, Te	0.0006	0.0004	0.0003	0.0006	0.0006
Thallium, Tl	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Thorium, Th	0.0005	0.0002	0.0008	<0.0002	0.0005
Uranium, U	0.0003	<0.0002	0.0003	<0.0002	0.0002
Zinc, Zn	0.5120	0.3645	0.6660	0.4168	0.3009

Note all values are mg/kg,, pH is dimensionless, - not measured.

3.8 LEACHATE RESULTS FOR FINE GRAINED SAMPLES USING BUFFERED SOLVENT

This experiment simulates the processes of extraction in acidic carbon dioxide saturated groundwater. The results of the leachate experiment are shown in Tables 3.14 - 3.16. The samples were grouped by rock types; alluvium, eastern clay conglomerate and western channel horizon.

Table 3.14 **Fine leachate samples from the alluvium (using NaOAc/HOAc)**

Hydrochemical characteristic	A851 F	A861 F	A918 F	A930 F	930 FD	939 F
Ratio	49.56	49.65	51.17	50.43	50.50	49.65
Major ions						
Potassium, K	79	68	91	157	168	210
Magnesium, Mg	127	97	134	102	106	76
Calcium, Ca	268	209	1240	151	145	662
Iron, Fe	<5	<5	<5	<5	<5	<5
Manganese, Mn	3.8	<2.5	4.4	15.1	12.9	7.2
Strontium, Sr	3	2	5	2	2	3
Trace elements						
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.002
Barium, Ba	6.045	7.877	23.457	5.131	4.692	4.727
Beryllium, Be	0.010	0.015	0.025	0.029	0.012	0.029
Bismuth, Bi	0.000	0.000	0.003	<0.0005	0.001	<0.0005
Cadmium, Cd	0.001	<0.0005	0.006	0.006	<0.0005	0.003
Chromium, Cr	0.074	0.066	0.099	0.091	0.099	0.100
Cobalt, Co	0.283	0.263	0.421	1.102	1.051	0.600
Copper, Cu	0.018	0.050	0.060	0.070	0.030	0.058
Lead, Pb	<0.0005	0.002	0.006	0.008	<0.0005	0.009
Molybdenum, Mo	<0.0005	<0.0005	<0.0005	<0.0005	0.001	<0.0005
Nickel, Ni	0.078	0.069	0.161	0.110	0.101	0.115
Selenium, Se	0.012	0.009	0.005	0.013	<0.0005	<0.0005
Silver, Ag	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Tellurium, Te	<0.0005	<0.0005	<0.0005	0.005	0.011	<0.0005
Thallium, Tl	0.002	0.000	0.001	0.004	0.002	<0.0005
Thorium, Th	0.001	0.002	0.002	0.002	0.002	0.000
Uranium, U	0.002	0.003	0.008	0.004	0.003	0.002
Zinc, Zn	0.557	0.684	0.497	0.684	0.698	0.449

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.15 **Fine leachate samples from the eastern clay conglomerate (using NaOAc/HOAc)**

Hydrochemical characteristic	A827F	A837F	A841F	A853 F	A865 F
Ratio	50.41	49.69	45.39	47.28	48.16
Major ions					
Potassium, K	27	51	140	419	135
Magnesium, Mg	112	74	246	532	152
Calcium, Ca	1599	174	6190	709	332
Iron, Fe	<5	<5	<5	<5	<5
Manganese, Mn	3.10	<2.5	<2.5	6.7	<2.5
Strontium, Sr	4	2	9	6	3
Trace elements					
Antimony, Sb	0.001	<0.0005	0.000	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	43.893	6.355	80.582	6.509	7.230
Beryllium, Be	0.005	0.007	0.002	0.006	0.006
Bismuth, Bi	0.001	<0.0005	0.001	<0.0005	0.001
Cadmium, Cd	0.006	<0.0005	<0.0005	0.001	0.002
Chromium, Cr	0.073	0.105	0.118	0.074	0.082
Cobalt, Co	0.270	0.224	0.037	0.298	0.226
Copper, Cu	0.034	0.016	0.059	0.028	0.042
Lead, Pb	0.019	0.005	<0.0005	0.002	0.004
Molybdenum, Mo	<0.0005	0.000	0.005	0.001	<0.0005
Nickel, Ni	0.091	0.092	0.167	0.074	0.029
Selenium, Se	<0.0005	<0.0005	0.009	<0.0005	0.036
Silver, Ag	0.002	<0.0005	<0.0005	<0.0005	0.002
Tellurium, Te	<0.0005	<0.0005	0.003	0.001	<0.0005
Thallium, Tl	0.001	0.001	0.003	<0.0005	<0.0005
Thorium, Th	<0.0005	0.000	0.003	0.001	0.002
Uranium, U	0.002	0.003	0.003	0.003	0.011
Zinc, Zn	0.759	0.629	0.193	0.695	0.501

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.15(cont.) **Fine leachate samples from the eastern clay conglomerate (using NaOAc/HOAc)**

Hydrochemical characteristic	A888F	A888FD	A898 F	A908F	A920 F	932 F
Ratio	49.76	50.36	49.44	49.31	50.52	50.79
Major ions						
Potassium, K	77	82	48	120	615	114
Magnesium, Mg	91	93	125	99	286	52
Calcium, Ca	106	250	238	574	398	202
Iron, Fe	<5	<5	<5	<5	<5	<5
Manganese, Mn	2.7	2.9	2.8	5.2	3.8	3.0
Strontium, Sr	4	4	4	7	5	2
Trace elements						
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	9.205	8.993	126.305	36.088	34.837	4.357
Beryllium, Be	0.015	0.020	0.016	0.005	0.011	0.025
Bismuth, Bi	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cadmium, Cd	0.002	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Chromium, Cr	0.142	0.069	0.073	0.071	0.086	0.107
Cobalt, Co	0.172	0.172	0.265	0.112	0.244	0.351
Copper, Cu	0.015	0.022	0.092	0.035	0.048	0.067
Lead, Pb	0.001	0.002	0.006	0.001	0.005	0.004
Molybdenum, Mo	<0.0005	0.001	<0.0005	<0.0005	<0.0005	0.001
Nickel, Ni	0.082	0.087	0.125	0.106	0.103	0.102
Selenium, Se	<0.0005	0.024	<0.0005	0.028	0.029	0.002
Silver, Ag	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Tellurium, Te	<0.0005	<0.0005	<0.0005	<0.0005	0.007	0.002
Thallium, Tl	0.001	0.001	0.003	0.001	0.003	0.006
Thorium, Th	0.002	0.002	0.001	<0.0005	<0.0005	0.001
Uranium, U	0.002	0.005	0.003	0.004	0.006	0.002
Zinc, Zn	0.619	0.531	0.574	0.531	0.487	0.692

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.16 **Fine leachate samples from the western channel horizon (using NaOAc/HOAc)**

Hydrochemical characteristic	A828F	A840F	A840FD	A844F	A856 F	A878 F
Ratio	51.08	50.49	50.70	50.16	49.78	49.14
Major ions						
Potassium, K	16	319	354	99	72	27
Magnesium, Mg	59	554	494	84	82	126
Calcium, Ca	140	2760	3059	185	147	905
Iron, Fe	<5	<5	<5	<5	<5	<5
Manganese, Mn	<2.5	<2.5	<2.5	<2.5	<2.5	3.0
Strontium, Sr	2	9	10	3	2	8
Trace elements						
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	8.754	3.626	3.440	6.714	2.183	81.906
Beryllium, Be	0.009	0.005	0.004	0.008	0.008	0.016
Bismuth, Bi	<0.0005	<0.0005	0.002	0.001	0.001	0.000
Cadmium, Cd	0.004	<0.0005	0.003	0.002	<0.0005	<0.0005
Chromium, Cr	0.081	0.086	0.088	0.079	0.070	0.057
Cobalt, Co	0.236	0.181	0.185	0.177	0.128	0.211
Copper, Cu	0.040	0.031	0.027	0.042	0.025	0.071
Lead, Pb	0.010	0.002	0.001	0.002	0.001	0.003
Molybdenum, Mo	<0.0005	0.001	0.002	<0.0005	<0.0005	<0.0005
Nickel, Ni	0.071	0.092	0.099	0.037	0.022	0.137
Selenium, Se	<0.0005	0.023	0.045	0.005	0.016	0.029
Silver, Ag	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Tellurium, Te	<0.0005	0.003	<0.0005	<0.0005	0.001	0.002
Thallium, Tl	<0.0005	0.001	<0.0005	<0.0005	<0.0005	<0.0005
Thorium, Th	0.002	0.001	0.002	0.001	0.001	<0.0005
Uranium, U	0.005	0.005	0.006	0.005	0.005	0.007
Zinc, Zn	1.247	0.504	0.566	0.541	0.524	0.575

Note all values are mg/kg,, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.16(cont.) **Fine leachate samples from the western channel horizon (using NaOAc/HOAc)**

Hydrochemical characteristic	A890 F	A900 F	A910F	933 F	933 FR	940 F	940 FR
Ratio	49.33	50.01	50.15	50.94	50.94	50.71	50.71
Major ions							
Potassium, K	41	64	86	83	86	85	87
Magnesium, Mg	129	112	96	97	109	80	82
Calcium, Ca	215	179	223	147	154	226	236
Iron, Fe	<5	<5	<5	<5	<5	<5	<5
Manganese, Mn	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Strontium, Sr	2	2	2	1	1	2	2
Trace elements							
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	30.190	11.777	3.291	3.729	3.803	10.871	10.868
Beryllium, Be	0.014	0.007	0.010	0.023	0.021	0.015	0.013
Bismuth, Bi	<0.0005	<0.0005	<0.0005	0.001	<0.0005	<0.0005	0.001
Cadmium, Cd	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Chromium, Cr	0.075	0.079	0.101	0.092	0.099	0.093	0.097
Cobalt, Co	0.176	0.127	0.142	0.283	0.286	0.293	0.290
Copper, Cu	0.034	0.060	0.040	0.062	0.061	0.051	0.059
Lead, Pb	0.002	0.005	0.004	0.002	0.008	0.008	0.009
Molybdenum, Mo	<0.0005	<0.0005	0.001	<0.0005	<0.0005	<0.0005	<0.0005
Nickel, Ni	0.039	0.035	0.058	0.053	0.045	0.094	0.086
Selenium, Se	0.029	0.002	0.040	<0.0005	0.035	<0.0005	<0.0005
Silver, Ag	<0.0005	<0.0005	0.001	<0.0005	0.001	<0.0005	0.001
Tellurium, Te	<0.0005	<0.0005	0.001	0.001	0.003	0.001	<0.0005
Thallium, Tl	0.002	0.005	0.003	0.005	0.002	0.002	0.003
Thorium, Th	0.002	0.001	0.001	0.002	0.001	0.002	0.003
Uranium, U	0.003	0.004	0.003	0.003	0.004	0.004	0.006
Zinc, Zn	0.502	0.530	11.218	0.573	0.559	0.460	0.528
Ytterbium, Yb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.001

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

3.9 LEACHATE RESULTS FOR COARSE GRAINED SAMPLES USING BUFFERED SOLVENT

This extraction was used to compare the effect of grain size of the samples as all conditions except the grainsize were constant. The results of the leachate experiment are shown in Tables 3.17 - 3.19. The samples were grouped by rock types; alluvium, eastern clay conglomerate and western channel horizon.

Table 3.17 **Coarse leachate samples from the alluvium (using NaOAc/HOAc)**

Hydrochemical characteristic	A851C	A851 CR	A861C	A918 C	A930 C	A930 CD	939 C
Ratio	41.08	41.08	21.15	45.14	44.19	48.18	50.31
Major ions							
Potassium, K	59	58	24	52	64	72	168
Magnesium, Mg	113	119	30	104	86	78	80
Calcium, Ca	220	224	74	2020	124	144	653
Iron, Fe	<5	<5	<5	<5	<5	<5	<5
Manganese, Mn	3.0	3.4	<2.5	3.2	7.2	7.7	8.0
Strontium, Sr	3	3	1	4	1	2	3
Trace elements							
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	0.001	<0.0005	<0.0005
Barium, Ba	4.585	4.198	2.422	17.947	4.883	4.961	4.764
Beryllium, Be	0.009	0.005	0.008	0.012	0.020	0.025	0.019
Bismuth, Bi	<0.0005	<0.0005	<0.0005	<0.0005	0.000	0.000	<0.0005
Cadmium, Cd	<0.0005	<0.0005	0.001	<0.0005	<0.0005	0.002	<0.0005
Chromium, Cr	0.053	0.073	0.040	0.084	0.206	0.090	0.097
Cobalt, Co	0.152	0.142	0.061	0.115	0.209	0.217	0.521
Copper, Cu	0.037	0.004	0.023	0.039	0.072	0.068	0.058
Lead, Pb	<0.0005	<0.0005	0.001	0.001	0.004	0.007	0.008
Molybdenum, Mo	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Nickel, Ni	0.048	0.044	0.039	0.116	0.084	0.099	0.133
Selenium, Se	<0.0005	0.014	0.010	<0.0005	0.022	<0.0005	<0.0005
Silver, Ag	<0.0005	<0.0005	<0.0005	<0.0005	0.001	<0.0005	<0.0005
Tellurium, Te	<0.0005	<0.0005	<0.0005	0.001	<0.0005	0.006	<0.0005
Thallium, Tl	0.000	<0.0005	0.001	0.001	0.001	0.001	0.004
Thorium, Th	0.001	0.002	0.000	0.001	0.001	0.002	0.002
Uranium, U	0.002	<0.0005	0.002	0.002	0.003	0.004	0.004
Zinc, Zn	0.490	0.375	0.225	0.700	0.776	1.357	0.519

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.18 **Coarse leachate samples from the eastern clay conglomerate (using NaOAc/HOAc)**

Hydrochemical characteristic	A827C	A837C	A841C	A853 C	A865 C
Ratio	45.30	33.86	43.15	38.86	49.92
Major ions					
Potassium, K	14	29	109	245	151
Magnesium, Mg	81	63	219	428	123
Calcium, Ca	2151	135	5530	578	206
Iron, Fe	<5	<5	<5	<5	<5
Manganese, Mn	<2.5	<2.5	2.8	3.4	<2.5
Strontium, Sr	3	2	9	5	2
Trace elements					
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	0.002	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	24.576	4.639	79.224	3.603	3.392
Beryllium, Be	0.002	0.007	0.001	0.005	0.005
Bismuth, Bi	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cadmium, Cd	0.003	<0.0005	<0.0005	0.002	<0.0005
Chromium, Cr	0.068	0.057	0.080	0.061	0.071
Cobalt, Co	0.076	0.066	0.034	0.059	0.011
Copper, Cu	0.015	0.029	0.052	0.020	0.041
Lead, Pb	0.017	0.007	<0.0005	<0.0005	0.003
Molybdenum, Mo	<0.0005	<0.0005	0.003	0.012	<0.0005
Nickel, Ni	0.057	0.073	0.154	0.038	0.025
Selenium, Se	0.036	0.026	0.019	<0.0005	0.007
Silver, Ag	<0.0005	0.000	<0.0005	0.001	<0.0005
Tellurium, Te	0.002	<0.0005	0.001	<0.0005	0.002
Thallium, Tl	0.001	0.001	0.001	0.001	0.001
Thorium, Th	0.001	0.000	0.001	0.001	0.001
Uranium, U	0.001	0.003	0.003	0.003	0.008
Zinc, Zn	1.004	0.418	0.297	0.472	0.552

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.18(cont.) **Coarse leachate samples from the eastern clay conglomerate (using NaOAc/HOAc)**

Hydrochemical characteristic	A888 C	A888CD	A898 C	A898 CR	A908C	A920 C	932 C
Ratio	47.04	44.46	45.19	45.19	48.99	37.12	50.08
Major ions							
Potassium, K	41	64	23	23	98	402	44
Magnesium, Mg	80	79	67	99	110	153	48
Calcium, Ca	245	239	168	187	505	200	168
Iron, Fe	<5	<5	<5	<5	<5	<5	<5
Manganese, Mn	2.7	<2.5	<2.5	<2.5	4.4	<2.5	<2.5
Strontium, Sr	3	3	3	3	6	3	1
Trace elements							
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	8.367	7.066	100.446	99.123	28.360	19.771	3.512
Beryllium, Be	0.013	0.004	0.009	0.009	0.003	0.006	0.019
Bismuth, Bi	<0.0005	0.001	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cadmium, Cd	0.001	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.003
Chromium, Cr	0.074	0.066	0.062	0.085	0.075	0.062	0.088
Cobalt, Co	0.111	0.100	0.100	0.102	0.028	0.074	0.150
Copper, Cu	0.045	0.003	0.067	0.075	0.018	0.041	0.059
Lead, Pb	0.005	<0.0005	0.001	0.003	<0.0005	0.005	0.006
Molybdenum, Mo	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.001
Nickel, Ni	0.059	0.062	0.069	0.067	0.065	0.037	0.083
Selenium, Se	<0.0005	<0.0005	<0.0005	0.001	0.005	0.001	<0.0005
Silver, Ag	<0.0005	<0.0005	<0.0005	<0.0005	0.000	0.000	<0.0005
Tellurium, Te	<0.0005	<0.0005	<0.0005	0.001	<0.0005	0.002	0.004
Thallium, Tl	0.001	0.001	0.003	<0.0005	0.000	0.002	0.004
Thorium, Th	0.002	<0.0005	0.001	<0.0005	0.001	0.001	0.002
Uranium, U	0.005	0.002	0.003	0.001	0.006	0.004	0.002
Zinc, Zn	0.546	0.390	0.498	0.559	0.448	0.430	0.665

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.19 **Coarse leachate samples from the western channel horizon (using NaOAc/HOAc)**

Hydrochemical characteristic	A828C	A840C	A840CD	A844C	A856 C
Ratio	31.28	48.14	30.35	46.17	15.62
Major ions					
Potassium, K	3	228	229	80	42
Magnesium, Mg	34	576	433	68	39
Calcium, Ca	83	4404	1969	384	64
Iron, Fe	<5	<5	<5	<5	<5
Manganese, Mn	<2.5	<2.5	<2.5	<2.5	<2.5
Strontium, Sr	1	10	6	2	1
Trace elements					
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	0.001	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	4.618	2.623	1.986	12.621	0.813
Beryllium, Be	0.004	0.004	0.002	0.005	0.003
Bismuth, Bi	0.001	<0.0005	0.001	0.000	<0.0005
Cadmium, Cd	0.001	0.003	0.001	<0.0005	0.000
Chromium, Cr	0.052	0.095	0.036	0.074	0.025
Cobalt, Co	0.023	0.029	0.018	0.018	0.007
Copper, Cu	0.019	0.022	0.015	0.037	0.007
Lead, Pb	0.009	0.003	0.002	0.003	0.000
Molybdenum, Mo	<0.0005	0.002	0.000	<0.0005	<0.0005
Nickel, Ni	0.036	0.111	0.049	0.038	0.008
Selenium, Se	0.034	0.075	0.016	0.003	<0.0005
Silver, Ag	<0.0005	<0.0005	0.000	<0.0005	<0.0005
Tellurium, Te	0.005	0.002	0.002	<0.0005	<0.0005
Thallium, Tl	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Thorium, Th	0.001	0.001	0.001	0.002	0.001
Uranium, U	0.003	0.001	0.003	0.003	0.001
Zinc, Zn	1.383	0.441	0.321	0.872	0.197

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

Table 3.19(cont.) **Coarse leachate samples from the western channel horizon (using NaOAc/HOAc)**

Hydrochemical characteristic	A890 C	A900 C	A900 CR	A910C	933 C	940 C
Ratio	42.71	45.21	45.21	19.23	41.55	51.30
Major ions						
Potassium, K	23	66	69	61	37	103
Magnesium, Mg	66	104	99	59	92	100
Calcium, Ca	147	160	150	55	127	763
Iron, Fe	<5	<5	<5	<5	<5	<5
Manganese, Mn	<2.5	<2.5	<2.5	<2.5	<2.5	4.4
Strontium, Sr	1	2	2	1	1	3
Trace elements						
Antimony, Sb	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Arsenic, As	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Barium, Ba	9.662	11.125	10.534	1.904	2.844	8.912
Beryllium, Be	0.009	0.006	0.004	0.003	0.017	0.016
Bismuth, Bi	<0.0005	<0.0005	0.001	<0.0005	<0.0005	<0.0005
Cadmium, Cd	0.001	<0.0005	0.002	0.000	0.001	0.007
Chromium, Cr	0.074	0.090	0.071	0.031	0.076	0.092
Cobalt, Co	0.028	0.017	0.014	0.048	0.092	0.486
Copper, Cu	0.022	0.054	0.076	0.011	0.058	0.062
Lead, Pb	0.002	0.005	0.006	<0.0005	0.004	0.010
Molybdenum, Mo	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Nickel, Ni	0.024	0.028	0.033	0.035	0.037	0.123
Selenium, Se	<0.0005	0.023	0.011	0.018	0.030	<0.0005
Silver, Ag	<0.0005	<0.0005	0.001	<0.0005	0.000	<0.0005
Tellurium, Te	<0.0005	0.002	<0.0005	<0.0005	<0.0005	0.003
Thallium, Tl	<0.0005	<0.0005	<0.0005	<0.0005	0.002	0.003
Thorium, Th	<0.0005	<0.0005	0.002	0.001	0.002	0.001
Uranium, U	0.003	0.004	0.002	0.002	0.002	0.005
Zinc, Zn	0.486	0.630	0.515	0.225	0.690	0.534

Note all values are mg/kg, - not measured. Ratio is the ratio of weight of NaOAc/HOAc to sample used.

3.10 LEACHING WITH TIME

This simulated the extraction process with time. Results of the leachate tests are shown in Tables 3.20-21.

Table 3.20 **Concentration of eastern clay conglomerate leachate solution with time**

Hydrochemical characteristic				
Minutes saturation	0	1	5	10
Sodium, Na	14.663	16.597	15.932	14.260
Potassium, K	1.395	1.636	1.761	1.786
Magnesium, Mg	0.845	1.009	0.979	0.752
Calcium, Ca	1.808	3.000	1.944	2.323
Iron, Fe	<0.001	0.158	<0.001	<0.001
Manganese, Mn	0.00065	0.00098	0.00166	0.00196
Strontium, Sr	0.01705	0.04197	0.03209	0.03296
Trace elements				
Antimony, Sb	0.00003	0.00003	0.00002	0.00004
Arsenic, As	0.00025	0.00034	0.00031	0.00034
Barium, Ba	0.01597	0.04026	0.03607	0.03735
Beryllium, Be	0.00002	0.00003	0.00003	0.00002
Bismuth, Bi	<0.00001	<0.00001	<0.00001	<0.00001
Cadmium, Cd	0.00003	0.00003	0.00003	0.00005
Chromium, Cr	0.00097	0.00121	0.00110	0.00094
Cobalt, Co	0.00003	0.00017	0.00034	0.00037
Copper, Cu	0.03596	0.03131	0.03192	0.09844
Lead, Pb	<0.00001	0.00002	0.00001	0.00002
Molybdenum, Mo	0.00002	0.00004	0.00003	0.00002
Nickel, Ni	0.00174	0.00302	0.00696	0.00720
Selenium, Se	0.00133	0.00145	0.00123	0.00135
Silver, Ag	0.00002	0.00002	0.00002	0.00002
Tellurium, Te	0.00008	0.00018	0.00025	0.00015
Thallium, Tl	0.00001	0.00002	0.00002	0.00002
Thorium, Th	0.00001	<0.00001	<0.00001	<0.00001
Uranium, U	<0.00001	<0.00001	<0.00001	<0.00001
Zinc, Zn	0.01164	0.01117	0.01980	0.03321

Note all values are mg/kg, - not measured.

Table 3.20(cont.) **Concentration of eastern clay conglomerate leachate solution with time**

Hydrochemical characteristic				
Minutes saturation	30	60	150	180
Sodium, Na	18.89	15.73	16.39	18.08
Potassium, K	1.917	2.131	2.228	2.255
Magnesium, Mg	0.929	1.019	1.083	1.101
Calcium, Ca	2.696	2.968	3.878	3.814
Iron, Fe	<0.001	0.158	<0.001	<0.001
Manganese, Mn	<0.0001	0.0001	0.0036	0.0034
Strontium, Sr	0.0396	0.0419	0.0497	0.0475
Trace elements				
Antimony, Sb	0.00001	0.00001	0.00003	0.00003
Arsenic, As	0.00005	0.00003	0.00038	0.00035
Barium, Ba	0.00331	0.00627	0.00492	0.00527
Beryllium, Be	<0.00001	<0.00001	0.00004	0.00003
Bismuth, Bi	<0.00001	<0.00001	<0.00001	<0.00001
Cadmium, Cd	0.00001	<0.00001	0.00006	0.00006
Chromium, Cr	0.00051	0.00064	0.00094	0.00087
Cobalt, Co	0.00011	0.00014	0.00050	0.00046
Copper, Cu	0.00145	0.00230	0.05394	0.05293
Lead, Pb	0.00031	0.00047	0.00001	0.00001
Molybdenum, Mo	0.00004	0.00006	0.00003	0.00002
Nickel, Ni	0.00040	0.00026	0.00002	0.00002
Selenium, Se	0.00010	0.00017	0.00130	0.00140
Silver, Ag	<0.00001	<0.00001	0.00002	0.00001
Tellurium, Te	0.00002	0.00001	0.00025	0.00021
Thallium, Tl	<0.00001	<0.00001	0.00003	0.00003
Thorium, Th	0.00002	0.00001	<0.00001	<0.00001
Uranium, U	<0.00001	<0.00001	<0.00001	<0.00001
Zinc, Zn	0.00379	0.00358	0.02450	0.01950

Note all values are mg/kg, - not measured.

Table 3.21 **Concentration of leachate solution with time (AET 828)**

Hydrochemical characteristic	LT1	LT2	LT4	LT5
Days of saturation	1	7	51	115
Ratio	44.98	48.06	54.17	49.65
Major ions				
Sodium, Na	0.73	0.58	-	-
Potassium, K	0.17	0.14	0.2222	0.184
Magnesium, Mg	0.27	0.35	0.6017	429
Calcium, Ca	1.15	1.19	1.3585	1587
Iron, Fe	<0.1	<0.1	0.13	1.115
Manganese, Mn	0.005	0.002	<0.05	0.021
Strontium, Sr	0.006	0.009	0.016	0.001
Trace elements				
Antimony, Sb	0.00003	0.00004	<0.00001	0.00003
Arsenic, As	0.0035	0.00030	<0.00001	0.00005
Barium, Ba	0.04551	0.04248	0.10819	0.15380
Beryllium, Be	0.00004	0.00003	0.00005	0.00002
Bismuth, Bi	<0.00001	<0.00001	<0.00001	<0.00001
Cadmium, Cd	0.00008	0.00007	<0.00001	0.00003
Chromium, Cr	0.00094	0.00082	0.00018	0.00066
Cobalt, Co	0.00062	0.00048	0.00068	0.00006
Copper, Cu	0.32740	0.07392	0.00201	0.00688
Lead, Pb	0.00017	0.00002	0.00074	<0.00001
Molybdenum, Mo	0.00002	0.00004	0.00008	0.00013
Nickel, Ni	<0.00001	0.00002	0.00056	0.00104
Selenium, Se	0.00135	0.00151	0.00061	0.00094
Silver, Ag	0.00003	0.00002	0.00008	0.00001
Tellurium, Te	0.00018	0.00022	0.00007	0.00034
Thallium, Tl	0.00002	0.00003	<0.00001	0.00001
Thorium, Th	<0.00001	<0.00001	0.00005	<0.00001
Uranium, U	<0.00001	<0.00001	0.0001	<0.00001
Zinc, Zn	0.03946	0.02427	0.0305	0.00999

Note all values are mg/kg, - not measured.

3.12 HYDROGEOLOGICAL RESULTS

Various tests were conducted on the overburden samples to assist in the estimation of the physical characteristics of the final aquifer.

3.12.1 GRAIN SIZE

The grain size distribution of the overburden sample enables calculation of the permeability of the material. The grainsize distribution was calculated by sieving the samples through a series of sieves with known apertures. The grain size of the sample also affected the reaction rate of the groundwater on the samples. The results of the grainsize analyses are shown in Table 3.22 and summarised in Table 3.23.

Table 3.22 **Hydraulic conductivities calculated by grainsize analysis**

		Hydraulic conductivity	
Sample	Lithology	m/s	m/d
LAET 939C	alluvium	2.55E-05	2.20
LAET 851C	alluvium	5.26E-05	4.54
LAET 930C	alluvium	7.14E-04	61.7
LAET 861C	alluvium	3.14E-03	271.1
LAET 918C	alluvium	5.70E-02	4927
LAET 920C	eastern clay conglomerate	2.02E-05	1.75
LAET 837C	eastern clay conglomerate	2.22E-05	1.92
LAET 908C	eastern clay conglomerate	2.49E-05	2.15
LAET 932C	eastern clay conglomerate	2.56E-05	2.21
LAET 827C	eastern clay conglomerate	2.79E-05	2.41
LAET 898C	eastern clay conglomerate	2.84E-05	2.46
LAET 853C	eastern clay conglomerate	3.56E-05	3.07
LAET 841C	eastern clay conglomerate	3.64E-05	3.15
LAET 865C	eastern clay conglomerate	1.32E-04	11.4
LAET 888C	eastern clay conglomerate	2.20E-04	19.0
LAET 828C	western channel horizon	1.28E-05	1.11
LAET 890C	western channel horizon	2.27E-05	1.96
LAET 856C	western channel horizon	2.34E-05	2.02
LAET 840C	western channel horizon	2.52E-05	2.18
LAET 844C	western channel horizon	2.60E-05	2.25
LAET 878C	western channel horizon	2.61E-05	2.26
LAET 933C	western channel horizon	3.35E-05	2.89
LAET 910C	western channel horizon	4.36E-05	3.77
LAET 900C	western channel horizon	4.80E-05	4.14
LAET 940C	western channel horizon	4.90E-05	4.23

Table 3.23 **Geometric and arithmetic mean for hydraulic conductivity**

Lithology	Geometric mean		Arithmetic mean	
	m/d	m/s	m/d	m/s
alluvium	60.71	7.03E-04	1053.40	1.22E-02
eastern clay conglomerate	3.38	3.92E-05	4.95	5.73E-05
western channel horizon	2.49	2.89E-05	2.68	3.10E-05

3.12.2 PERMEAMETER RESULTS

A selection of samples were tested using a customised permeameter shown in Figure 2.4 and Figure 2.5. The results from the permeameter can be compared with the predicted values from the grainsize analysis. The results of the permeameter are shown in Table 3.24.

Table 3.24 **Hydraulic conductivity results from permeameter**

Sample	Hydraulic Conductivity	
	m/d	m/s
ECC (1/6)	62.6	7.25E-04
1 ECC L1	6.18E-02	5339
1 ECC L1	2.90E-01	25028
13 ALL 6	8.34E-03	720.36
14 ALL 6	1.49E-02	1289
6 ECC L2	7.97E-04	68
6 ECC L2b	4.67E-03	403
6 ECC L2c	1.03E-02	890

Lithology	Geometric mean		Arithmetic mean	
	m/d	m/s	m/d	m/s
alluvium	963	1.12E-02	1005	1.16E-02
eastern clay conglomerate	1270	1.47E-02	6346	7.35E-02
western channel horizon	-	-	-	-

The permeameter was constructed from clear perspex and designed to allow observation of the physical changes to the material being tested. The observations through the perspex are documented below and photographically documented in Figures 3.2.

Prior to adding the water, the clasts were firm but friable. During the testing of the eastern clay conglomerate material (buff white gravel to pebble sized clasts, predominantly composed of fine sand and clay) started to break apart to clay and fine sand sized particles when immersed in the water. This increased the clay sized content of the eastern clay conglomerate and would reduce the porosity and permeability of the eastern clay conglomerate.

After 0 minutes

After 3 minutes 45 seconds

After 15 minutes

Figure 3.2

PHOTOGRAPHS OF WCH OVERBURDEN SUBMERGED IN WATER

3.13 MINERALOGY

During drilling the geologist examined and documented the mineralogy of the drilled rock samples in the field. These results are shown in Table 3.25.

In this study a selection of crushed rock samples were crushed further to a grainsize of less than 10µm and analysed by X-Ray Diffraction (XRD) to establish the major phases present in various overburden materials. The results of the XRD analyses are shown in Table 3.26.

Table 3.25 **Mineralogical results**

	AET 851	AET 861	AET 918	AET 930	AET 939
Bore hole	YJ-P187	YJ-P188	YJ-P194	YJ-P196	YJ-P198
Cross - section	13.95	13.95	14.45	15	15
Depth	0-2m	0-2m	0-2m	0-2m	0-2m
Strand	alluvium	alluvium	alluvium	SUR	alluvium
Colour	Red-Brown	Light-Brown	Light-Brown	Pink	Light-Brown
B.I.F. (%)	Trace	-	60	-	60
B.I.F. (Hematite) (%)	-	-	-	-	-
Clay (%)	-	10	-	95	-
Goethite (%)	-	-	-	-	-
Goethite - Limonite (%)	-	-	-	-	-
Goethite - Vitreous (%)	-	-	-	-	Trace
Hematite - Goethite (%)	60	40	10	5	20
Hematite - Ochrous (%)	-	-	-	-	-
Hematite - Siliceous (%)	20	40	-	-	-
Laterite (%)	-	-	-	-	-
Limonite (%)	-	-	-	-	-
Limonitic (%)	-	-	-	-	-
Pisolite (%)	Trace	-	20	-	-
Soil (%)	20	10	10	-	20

Table 3.25(cont.) **Mineralogical results**

	AET 827	AET 837	AET 841	AET 853	AET 865
Bore hole	YJ-P184	YJ-P185	YJ-P186	YJ-P187	YJ-P188
Cross - section	13.95	13.95	13.95	13.95	13.95
Depth	0-2m	0-2m	0-2m	4-6m	8-10m
Strand	LAT	LAT	LAT	LAT	LAT
Colour	Brown	Yellow	Light-Brown	Yellow-Brown	Light-Brown
B.I.F. (%)	-	-	20	10	-
B.I.F. (Hematite) (%)	-	-	-	-	-
Clay (%)	10	10	10	30	Trace
Goethite (%)	-	70	-	-	-
Goethite - Limonite (%)	-	-	-	-	-
Goethite - Vitreous (%)	30	-	-	-	-
Hematite - Goethite (%)	10	-	30	10	20
Hematite - Ochrous (%)	-	-	-	-	-
Hematite - Siliceous (%)	-	-	-	-	-
Laterite (%)	40	10	20	50	80
Limonite (%)	-	-	-	-	Trace
Limonitic (%)	-	-	-	-	-
Pisolite (%)	-	-	-	-	-
Soil (%)	10	10	20	-	-

Table 3.25(cont.) **Mineralogical results**

	AET 888	AET 898	AET 908	AET 920	AET 932
Bore hole	YJ-P191	YJ-P192	YJ-P193	YJ-P194	YJ-P197
Cross - section	14.45	14.45	14.45	14.45	15
Depth	0-2m	0-2m	0-2m	4-6.2m	0-2m
Strand	LAT	LAT	LAT	LAT	eastern clay conglomerate
Colour	Yellow	Yellow	Yellow-Brown	-	Red
B.I.F. (%)	-	-	-	-	-
B.I.F. (Hematite) (%)	-	-	-	-	20
Clay (%)	Trace	-	-	-	50
Goethite (%)	15	-	-	20	-
Goethite - Limonite (%)	-	60	-	-	-
Goethite - Vitreous (%)	-	20	-	-	-
Hematite - Goethite (%)	-	-	60	60	30
Hematite - Ochrous (%)	-	-	-	-	-
Hematite - Siliceous (%)	-	-	30	-	-
Laterite (%)	80	20	Trace	20	-
Limonite (%)	-	-	-	-	-
Limonitic (%)	-	-	-	-	-
Pisolite (%)	-	-	Trace	-	-
Soil (%)	5	-	10	-	-

Table 3.25(cont.) **Mineralogical results**

	AET 828	AET 840	AET 844	AET 856	AET 878
Bore hole	YJ-P184	YJ-P185	YJ-P186	YJ-P187	YJ-P190
Cross - section	13.95	13.95	13.95	13.95	14.45
Depth	2-4m	6-8.2m	6-8m	10-12m	0-2m
Strand	western channel horizon	western channel horizon	western channel horizon	western channel horizon	western channel horizon
Colour	Brown	Brown	Brown	Yellow-Brown	Red-Brown
B.I.F. (%)	-	-	-	-	-
B.I.F. (Hematite) (%)	-	-	-	-	-
Clay (%)	-	30	-	5	Trace
Goethite (%)	10	-	40	60	10
Goethite - Limonite (%)	-	-	-	-	-
Goethite - Vitreous (%)	65	50	55	30	70
Hematite - Goethite (%)	-	-	-	-	-
Hematite - Ochrous (%)	-	-	-	-	-
Hematite - Siliceous (%)	10	-	5	-	-
Laterite (%)	-	-	-	-	-
Limonite (%)	-	-	-	5	-
Limonitic (%)	-	20	-	-	-
Pisolite (%)	-	-	-	-	-
Soil (%)	-	-	-	-	20

Table 3.25(cont.) **Mineralogical results**

	AET 890	AET 900	AET 910	AET 933	AET 940
Bore hole	YJ-P191	YJ-P192	YJ-P193	YJ-P197	YJ-P198
Cross - section	14.45	14.45	14.45	15	15
Depth	4-6m	4-6m	4-6m	2-4m	2-4m
Strand	western channel horizon	western channel horizon	western channel horizon	western channel horizon	western channel horizon
Colour	Brown	-	Brown	Red	Brown
B.I.F. (%)	-	-	-	-	-
B.I.F. (Hematite) (%)	-	-	-	-	-
Clay (%)	Trace	-	-	60	-
Goethite (%)	50	30	20	-	20
Goethite - Limonite (%)	-	-	-	-	-
Goethite - Vitreous (%)	50	-	55	-	60
Hematite - Goethite (%)	-	30	-	30	-
Hematite - Ochrous (%)	-	-	10	-	-
Hematite - Siliceous (%)	-	20	5	-	5
Laterite (%)	-	20	-	-	-
Limonite (%)	-	-	-	-	-
Limonitic (%)	-	-	-	-	-
Pisolite (%)	-	-	10	10	5
Soil (%)	-	-	-	-	10

Table 3.26 **Clay Mineralogical results**

Minerals detected	Sample 1 Loc2 ECC	Sample 2 WCH Loc1	Sample 3 Loc1 WCH
Smectite †	Major	Dominant	Dominant
Kaolin ‡	Dominant	Major	Major
Quartz	Major	Major	Major
Microcline	Trace	Trace	?
Anatase	?	?	?
Goethite	-	-	Major
Hematite	trace	-	-

Notes Dominant (>50%), Major =10% but =50%), Trace (<approx.2%), ?=unconfirmed may be present in small amounts, - not present, † confirmed using clay speciation, ‡ may include kaolinite and dehydrated halloysite.

Chapter Four

INTERPRETATION

4.1 INTRODUCTION

In this section historical and laboratory results were used to calculate various parameters of the regional groundwater and overburden materials. The groundwater and rocks were studied further to establish their interrelationships and finally to establish system models of the area.

4.1.1 ROCK INTERPRETATION

The rock composition was compared with the average crustal values to identify any elements that were enriched within the study region. The distribution and correlation of the elements were studied to determine relationships with the strata or the mineralogy.

The chemical composition was studied further to establish methods of classifying the materials by their chemistry.

4.1.2 REGIONAL GROUNDWATER

The groundwaters were divided into subsets based on the aquifer they were from. Groundwaters from the same aquifer should have similar chemical compositions.

4.1.3 LEACHATE RESULTS

The results were used to establish the elements most likely to dissolve in the groundwater and be chemically available in the environment.

4.2 ROCK CHEMISTRY

The rock compositions were compared with the average crustal elemental values from Mason and Moore, (1982) shown in Table 4.2. This comparison was simplified using a method Geochemical Abundance Index (GAI). The relative enrichment factors are shown in Table 4.1. The GAI values of analysed samples are listed in the Table 4.3.

Table 4.1 **Corresponding degree of enrichment for GAI integers**

GAI	Enrichment factor	GAI	Enrichment factor
0	0 - 2 enrichment	1	3 - 6 fold enrichment
2	6 - 12 fold enrichment	3	12 - 24 fold enrichment
4	24 - 48 fold enrichment	5	48 – 97 fold enrichment
6	Greater then 97 fold enrichment		

*Note * Table after Thomas and Evans 1998, p.26.*

Table 4.2 **Comparison of average rock samples with the average crustal values.**

Chemical characteristics	Average Crustal Values*	Alluvium	Eastern clay conglomerate	Western channel horizon
Major Constituents				
Aluminium, as Al_2O_3	81300	109560	123540	73420
Magnesium, as MgO	20900	1560	3340	1980
Calcium, CaO*	36300	2040	3320	2120
Iron, Fe	50000	361980	380300	503200
Manganese, as Mn	950	260	220	290
Phosphorus, P	1050	266	206	344
Strontium, Sr	375	15	21	17
Sulphur, S	260	154	217	121
Silica, as SiO_2	277200	301360	214790	111779
Titanium, Ti	4400	4201	5646	4046
Trace elements				
Antimony, Sb	0.2	6.3	4.4	1.7
Arsenic, As	1.8	12.0	14.9	12.0
Barium, Ba	3	103	277	76
Beryllium, Be	2.8	1.9	1.9	1.8
Bismuth, Bi	0.2	0.5	0.3	0.1
Cadmium, Cd	0.2	0.1	0.1	0.1
Chromium, Cr	100	136	77	43
Copper, Cu	55	49	49	23
Lead, Pb	13	48	35	15
Molybdenum, Mo	1.5	4.4	5.1	4.2
Nickel, Ni	75	28	37	20
Selenium, Se	0.05	0.83	0.75	0.43
Silver, Ag	0.07	<0.01	<0.01	<0.01
Tellurium, Te	0.01	0.12	0.08	0.04
Thallium, Tl	0.5	0.3	0.2	0.1
Thorium, Th	7.2	17.9	16.3	7.5
Uranium, U	1.8	2.9	3.8	2.2
Zinc, Zn	70	46	29	15

*Note *Average Crustal values from Mason and Moore 1982, units mg/kg.*

Table 4.3 **Geochemical Abundance Index values for alluvium**

Chemical characteristics	AET 851 0-2m	AET 861 0-2m	AET 918 0-2m	AET 930 0-2m	AET 930D 0-2m	AET 939 0-2m
Major Constituents						
Aluminium, as Al_2O_3	0	0	0	0	-	0
Magnesium, as MgO	0	0	0	0	-	0
Calcium, CaO*	0	0	0	0	-	0
Iron, Fe	2	2	2	1	-	2
Manganese, as Mn	0	0	0	0	-	0
Phosphorus, P	0	0	0	0	-	0
Strontium, Sr	0	0	0	0	0	0
Sulphur, S	0	0	0	0	-	0
Silica, as SiO_2	0	0	0	0	-	0
Titanium, Ti	0	0	0	0	0	0
Trace elements						
Antimony, Sb	1	4	4	3	3	3
Arsenic, As	0	2	2	1	1	1
Barium, Ba	1	3	4	4	4	4
Beryllium, Be	0	0	0	0	0	0
Bismuth, Bi	1	1	0	0	0	0
Cadmium, Cd	0	0	0	0	0	0
Chromium, Cr	0	0	0	0	0	0
Copper, Cu	0	0	0	0	0	0
Lead, Pb	1	1	1	0	0	0
Molybdenum, Mo	1	1	1	0	0	0
Nickel, Ni	0	0	0	0	0	0
Selenium, Se	4	3	2	0	0	0
Silver, Ag	0	0	0	0	0	0
Tellurium, Te	3	3	3	2	2	2
Thallium, Tl	0	0	0	0	0	0
Thorium, Th	1	1	1	0	0	0
Uranium, U	0	1	0	0	0	0
Zinc, Zn	0	0	0	0	0	0

Note GAI values are dimentionless

Table 4.4 **Geochemical Abundance Index values for eastern clay conglomerate**

Chemical characteristics	AET 827 0-2m	AET 837 0-2m	AET 841 0-2m	AET 853 4-6m	AET 865 8-10m
Major Constituents					
Aluminium, as Al_2O_3	0	0	0	0	0
Magnesium, as MgO	0	0	0	0	0
Calcium, CaO*	0	0	0	0	0
Iron, Fe	2	2	2	1	2
Manganese, as Mn	0	0	0	0	0
Phosphorus, P	0	0	0	0	0
Strontium, Sr	0	0	0	0	0
Sulphur, S	0	0	0	0	0
Silica, as SiO_2	0	0	0	0	0
Titanium, Ti	0	0	0	0	0
Trace elements					
Antimony, Sb	3	3	3	4	4
Arsenic, As	1	2	2	1	2
Barium, Ba	5	3	6	4	3
Beryllium, Be	0	0	0	0	0
Bismuth, Bi	0	0	0	0	0
Cadmium, Cd	0	0	0	0	0
Chromium, Cr	0	0	0	0	0
Copper, Cu	0	0	0	0	0
Lead, Pb	0	0	1	1	1
Molybdenum, Mo	1	1	1	0	1
Nickel, Ni	0	0	0	0	0
Selenium, Se	3	3	3	1	2
Silver, Ag	0	0	0	0	0
Tellurium, Te	2	2	2	1	2
Thallium, Tl	0	0	0	0	0
Thorium, Th	0	0	0	0	1
Uranium, U	0	0	0	0	0
Zinc, Zn	0	0	0	0	0

Note GAI values are dimensionless

Table 4.4(cont.) **Geochemical Abundance Index values for eastern clay conglomerate**

Chemical characteristics	AET 888 0-2m	AET 888D 0-2m	AET 898 0-2m	AET 908 0-2m	AET 920 4-6.2m	AET 932 0-2m
Major Constituents						
Aluminium, as Al_2O_3	0	-	0	0	0	0
Magnesium, as MgO	0	-	0	0	0	0
Calcium, CaO*	0	-	0	0	0	0
Iron, Fe	2	-	2	2	2	2
Manganese, as Mn	0	-	0	0	0	0
Phosphorus, P	0	-	0	0	0	0
Strontium, Sr	0	0	0	0	0	0
Sulphur, S	0	-	0	0	0	0
Silica, as SiO_2	0	-	0	0	0	0
Titanium, Ti	0	0	0	0	0	0
Trace elements						
Antimony, Sb	3	3	2	3	3	4
Arsenic, As	2	2	2	2	2	2
Barium, Ba	3	3	6	5	5	3
Beryllium, Be	0	0	0	0	0	0
Bismuth, Bi	0	0	0	0	0	0
Cadmium, Cd	0	0	0	0	0	0
Chromium, Cr	0	0	0	0	0	0
Copper, Cu	0	0	0	0	0	0
Lead, Pb	1	1	0	0	1	1
Molybdenum, Mo	1	1	0	1	1	1
Nickel, Ni	0	0	0	0	0	0
Selenium, Se	3	3	3	0	0	3
Silver, Ag	0	0	0	0	0	0
Tellurium, Te	2	2	2	2	2	2
Thallium, Tl	0	0	0	0	0	0
Thorium, Th	1	1	0	0	0	0
Uranium, U	1	1	0	0	0	0
Zinc, Zn	0	0	0	0	0	0

Note GAI values are dimensionless

Table 4.5 **Geochemical Abundance Index values for weathered channel horizon**

Chemical characteristics	AET 828 2-4m	AET 840 6-8.2m	AET 844 6-8m	AET 844D 6-8m	AET 856 10-12m	AET 878 0-2m
Major Constituents						
Aluminium, as Al_2O_3	0	0	0	-	0	0
Magnesium, as MgO	0	0	0	-	0	0
Calcium, CaO*	0	0	0	-	0	0
Iron, Fe	2	2	2	-	2	2
Manganese, as Mn	0	0	0	-	0	0
Phosphorus, P	0	0	0	-	0	0
Strontium, Sr	0	0	0	0	0	0
Sulphur, S	0	0	0	-	0	0
Silica, as SiO_2	0	0	0	-	0	0
Titanium, Ti	0	0	0	0	0	0
Trace elements						
Antimony, Sb	1	1	2	1	1	2
Arsenic, As	2	2	2	2	2	2
Barium, Ba	3	2	3	3	2	6
Beryllium, Be	0	0	0	0	0	0
Bismuth, Bi	0	0	0	0	0	0
Cadmium, Cd	0	0	0	0	0	0
Chromium, Cr	0	0	0	0	0	0
Copper, Cu	0	0	0	0	0	0
Lead, Pb	0	0	0	0	0	0
Molybdenum, Mo	1	0	1	1	1	1
Nickel, Ni	0	0	0	0	0	0
Selenium, Se	3	2	2	2	2	3
Silver, Ag	0	0	0	0	0	0
Tellurium, Te	0	1	1	1	0	1
Thallium, Tl	0	0	0	0	0	0
Thorium, Th	0	0	0	0	0	0
Uranium, U	0	0	0	0	0	0
Zinc, Zn	0	0	0	0	0	0

Note GAI values are dimensionless

Table 4.5(cont.) **Geochemical Abundance Index values for weathered channel horizon**

Chemical characteristics	AET 890 4-6m	AET 900 4-6m	AET 910 4-6m	AET 933 2-4m	AET 940 2-4m
Major Constituents					
Aluminium, as Al_2O_3	0	0	0	0	0
Magnesium, as MgO	0	0	0	0	0
Calcium, CaO*	0	0	0	0	0
Iron, Fe	2	2	2	2	2
Manganese, as Mn	0	0	0	0	0
Phosphorus, P	0	0	0	0	0
Strontium, Sr	0	0	0	0	0
Sulphur, S	0	0	0	0	0
Silica, as SiO_2	0	0	0	0	0
Titanium, Ti	0	0	0	0	0
Trace elements					
Antimony, Sb	1	3	2	3	2
Arsenic, As	2	2	2	2	2
Barium, Ba	4	4	2	3	3
Beryllium, Be	0	0	0	0	0
Bismuth, Bi	0	0	0	0	0
Cadmium, Cd	0	0	0	0	0
Chromium, Cr	0	0	0	0	0
Copper, Cu	0	0	0	0	0
Lead, Pb	0	0	0	0	0
Molybdenum, Mo	1	1	1	0	1
Nickel, Ni	0	0	0	0	0
Selenium, Se	2	2	0	0	2
Silver, Ag	0	0	0	0	0
Tellurium, Te	0	2	1	1	1
Thallium, Tl	0	0	0	0	0
Thorium, Th	0	0	0	1	0
Uranium, U	0	0	0	0	0
Zinc, Zn	0	0	0	0	0

Note GAI values are dimensionless

Table 4.6 **Geochemical Abundance Index values for the regional rocks**

Chemical characteristics	Calcite mineralised Shale	Shale	BIF	Dolerite
Major Constituents				
Aluminium, as Al_2O_3	0	0	0	0
Magnesium, as MgO	0	1	1	0
Calcium, CaO*	2	0	0	0
Iron, Fe	0	1	1	0
Manganese, as Mn	0	0	0	0
Phosphorus, P	0	0	0	0
Strontium, Sr	0	0	0	0
Silica, as SiO_2	0	0	0	0
Titanium, Ti	0	0	0	0
Trace elements				
Antimony, Sb	1	0	1	2
Arsenic, As	0	0	0	0
Barium, Ba	2	4	3	2
Beryllium, Be	0	0	0	0
Bismuth, Bi	0	0	0	0
Cadmium, Cd	0	0	0	0
Chromium, Cr	0	0	0	0
Copper, Cu	0	0	0	0
Lead, Pb	0	0	1	0
Molybdenum, Mo	0	0	0	0
Nickel, Ni	0	0	0	0
Selenium, Se	0	0	0	0
Silver, Ag	0	0	0	0
Tellurium, Te	1	2	1	2
Thallium, Tl	0	0	0	0
Thorium, Th	0	0	0	0
Uranium, U	0	0	0	0
Zinc, Zn	0	0	0	0

Note GAI values are dimensionless

4.2.1 MAJOR ELEMENT ANALYSIS

Major element analyses of the overburden material were provided by Hamersley Iron. The analyses support the mineralogical evidence that:

- the upper part of the ore body and overburden are depleted in iron minerals.
- The eastern clay conglomerate and alluvium have higher amounts of clay minerals and therefore have a higher aluminium concentration than the ore body.

The GAI values (Table 4.3) show that iron is the only major element that is significantly enriched in all the rock samples and ranges between 25 % in one of the alluvium samples to 56 % in the weathered channel horizon. This is 5 to 11 times greater than the average crustal abundance (5 %). Iron is found at higher concentrations with increasing depth. Leaching and dilution by other rock types within the alluvium have reduced the proportion of iron in the eastern clay conglomerate and alluvium. High concentrations of iron were expected, as the material is the weathered part of an iron ore body.

Aluminium and silica concentrations increase towards the top of the sections (Figure 4.1 and 4.2). This is due to leaching of the more soluble elements and minerals from the upper horizons. Blanchard (1968) discussed the weathering of iron minerals such as hematite. His conclusion was that hematite will begin to weather under acidic conditions where sulphides are present but only at the surface. However, the analyses from the Yandi junction show very low sulphide concentrations. Humic acids are thought to have caused the low pH conditions for the weathering process of the hematite (Hall *et al.*, 1990). Waters below pH 7 and a low Eh would have been sufficient to dissolve significant amounts of iron.

Humic acid generation may have occurred as wood and other organic material decomposed and was replaced by goethite. Morris, Ramanaidou and Horwitz (1993) suggest that extremely low pH conditions existed, down to pH 2 or lower, during the formation of the CID. Acid was produced by the oxidation of soluble ferrous iron to insoluble ferric iron.

$$2Fe^{2+} + CH_2O + 2H_2O \; ? \quad 2Fe^{3+} + CH_4 + 2(OH)^-$$

$$Fe^{3+} + 2H_2O \; ? \quad FeOOH + 3H^+$$

Neutralisation of the hydroxy ions with the excess hydrogen ions gives a net production of 2 moles of acid for each ferrous ion that is oxidised. Morris *et al* (1993) suggest the strong acid condition would be aggressive to all non cellulose organic material and that could explain the lack of carbonate or phosphatic animal remnants.

The mottled colours of the upper horizons indicate weathering. The darker patches are unleached areas of the rock and the light parts are leached areas that are depleted in elements including iron. The more insoluble clay minerals remain, leaving silica and aluminium relatively enriched.

The weathering process weakens the rocks, which can be broken easily with a hammer.

Magnesium and titanium were slightly enriched and also appear to be associated with aluminium and silica. This can be seen in the correlations in Figure 4.14, and suggests that the elements are associated with clay minerals. Titanium was three times greater than the Earth's crustal abundance in sample AET 888, which was described as predominantly a laterite.

All cross sections show iron is relatively depleted in the upper regions. However, even depleted areas are still significantly enriched compared to the average crustal values.

Phosphorus and manganese show a close positive correlation with iron. These elements are probably associated with the iron minerals hematite and goethite.

Magnesium, calcium, carbonate and sulphate show positive correlation with each other and are associated primarily with evaporite minerals in the area such as dolomite, calcite and gypsum. Halite will also be present but sodium and chloride were not analysed in the rock samples.

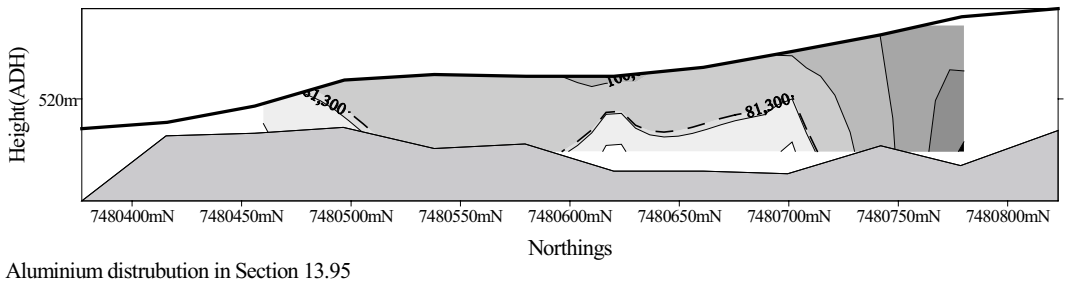
Table 4.7 **Summary of chemical characteristics of rock samples**

Chemical characteristics	Concentration range	Average	Average crustal value	Average GAI	Mineral association
Aluminium, as Al_2O_3	32,200 - 169,700	100,696	81,300	0	Clay (+goethite)
Magnesium, as MgO	800 - 11,800	2440	20,900	0	Clay and evaporite
Calcium, CaO*	500 - 18,200	2584	36,300	0	Clay and evaporite
Iron, Fe	228,800 - 559,400	425,796	50,000	2	Iron
Manganese, as Mn	100 - 500	256	950	0	Iron, goethite
Phosphorus, P	100 - 540	273	1,050	0	Iron
Strontium, Sr	7.9 - 40.9	18	375	0	Clay?
Sulphur, S	70 - 420	166	260	0	Clay and Iron
Silica, as SiO_2	71,500 - 457,100	190,900	277,200	0	Clay (+goethite)
Titanium, TiO_2	2,800 - 15,300	7296	4,400	0	Goethite

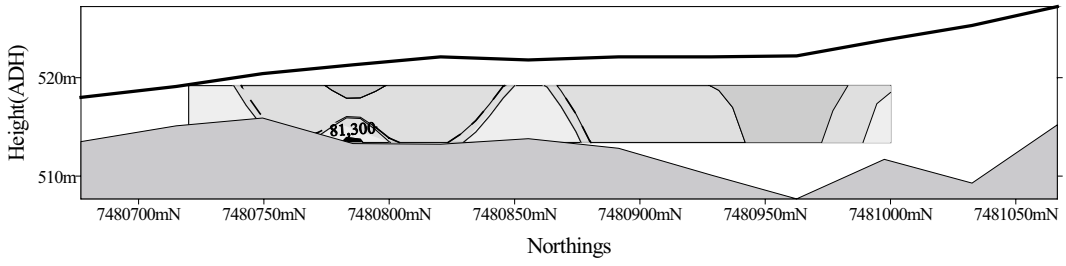
4.2.2 TRACE ELEMENTS

The GAI show that the trace elements antimony, arsenic, barium, bismuth, gallium, germanium, lead, mercury, molybdenum, palladium, selenium, tantalum, tellurium, thorium, tin, vanadium and zirconium are significantly enriched in parts of the overburden.

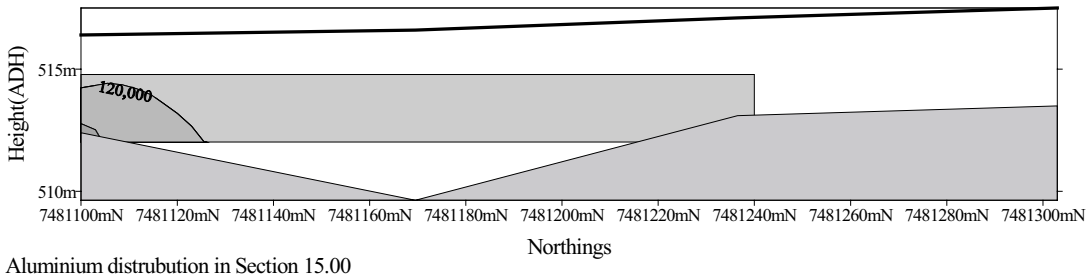
Correlations (Figures 4.13 – 4.14) and the elemental distribution in sections (Figures 4.1 – 4.12) show that many of the trace elements have similar trends and can be grouped together by their association with major elements and major mineral phases present.



Aluminium distrubution in Section 13.95



Aluminium distrubution in Section 14.45



Aluminium distrubution in Section 15.00

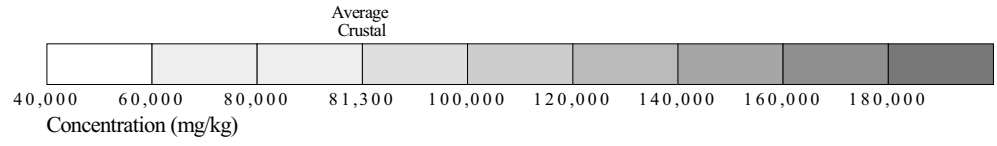
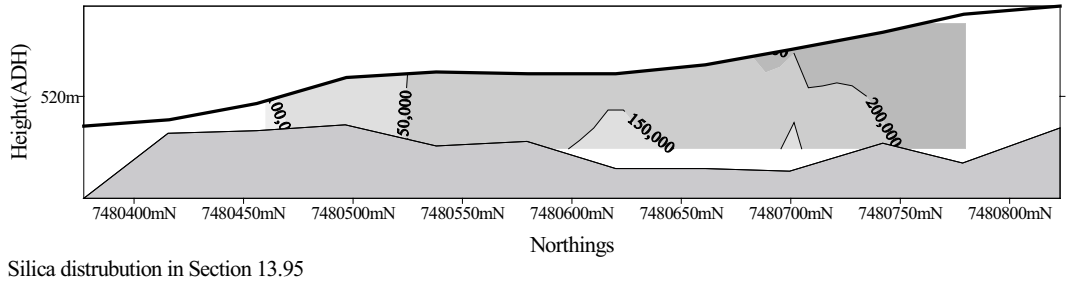
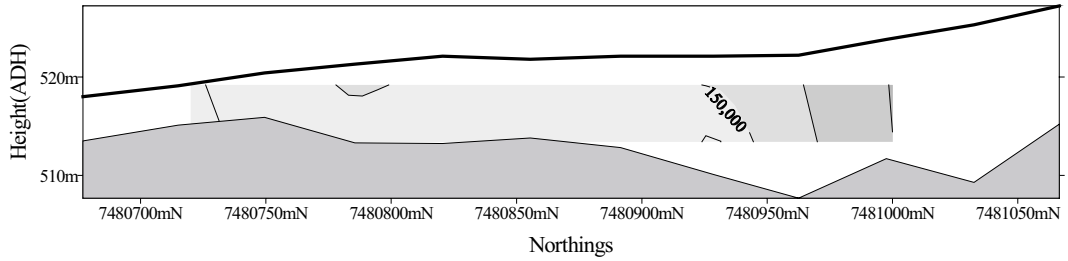


Figure 4.1

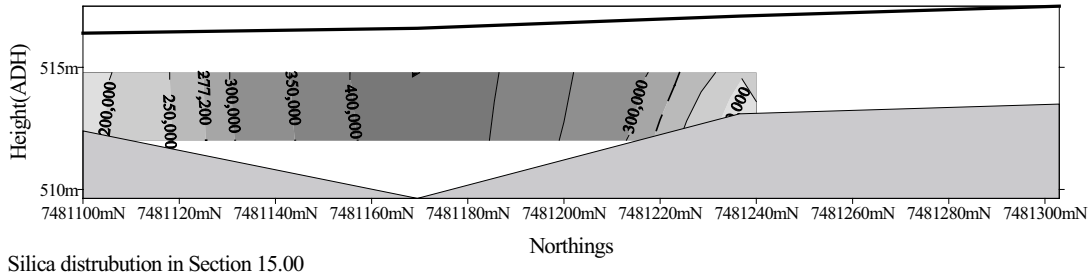
ALUMINIUM DISTRIBUTION IN THE SECTIONS (as Al_2O_3)



Silica distrubution in Section 13.95



Silica distrubution in Section 14.45



Silica distrubution in Section 15.00

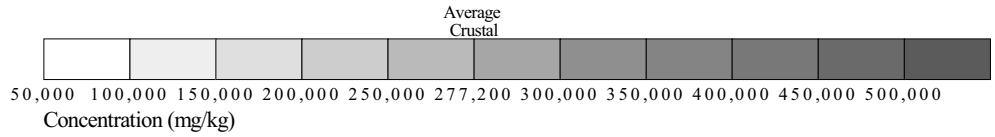
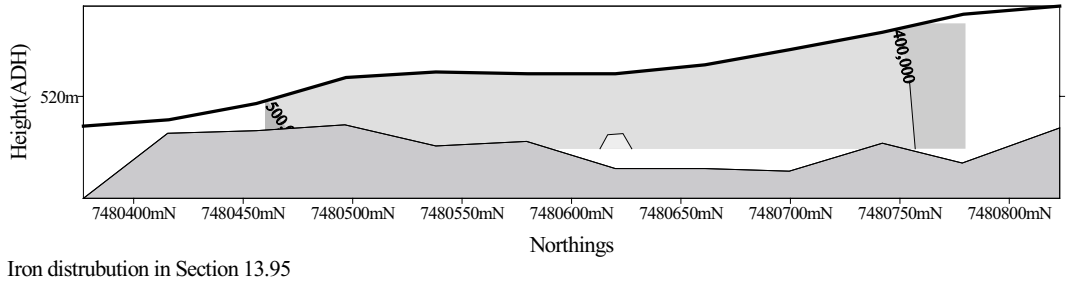
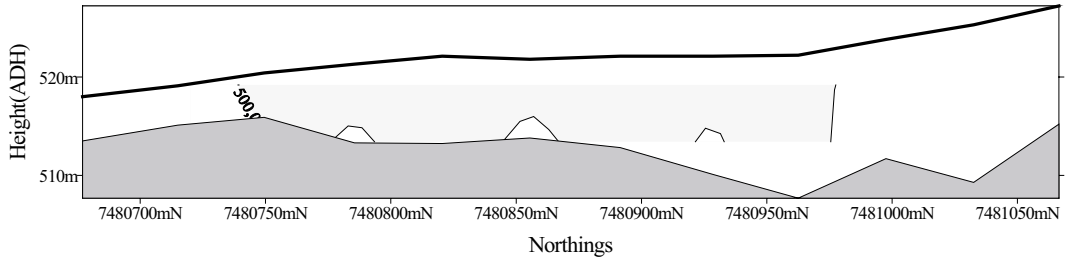


Figure 4.2

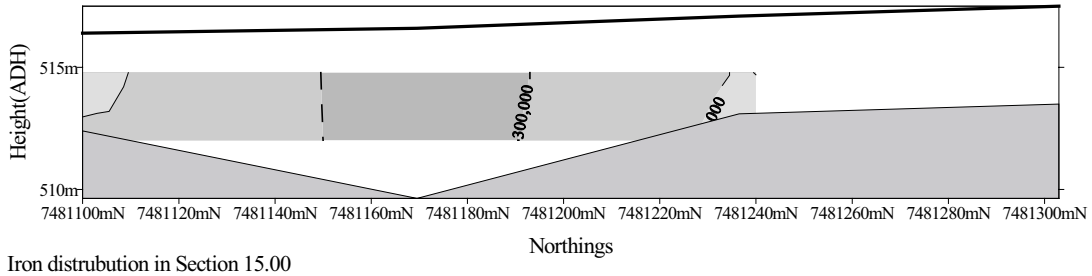
SILICA DISTRIBUTION IN THE SECTIONS (as SiO_2)



Iron distrubution in Section 13.95



Iron distrubution in Section 14.45



Iron distrubution in Section 15.00

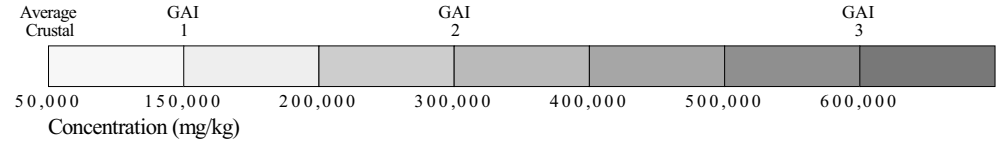
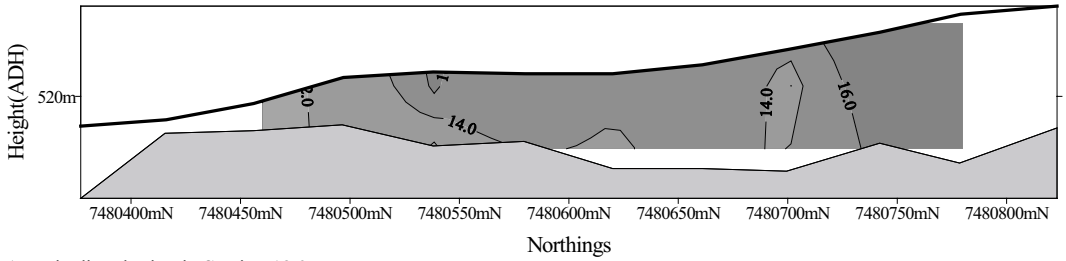
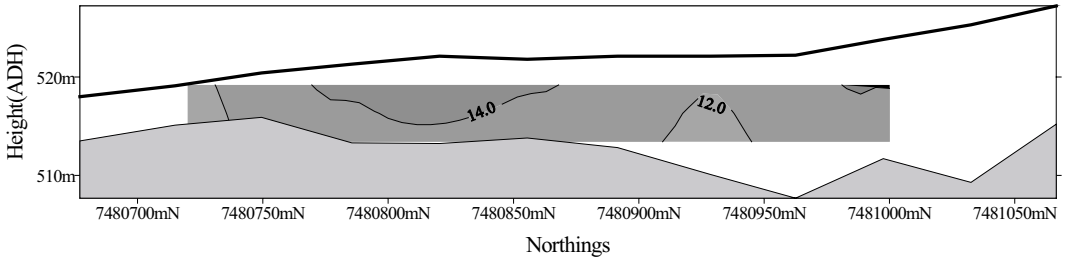


Figure 4.3

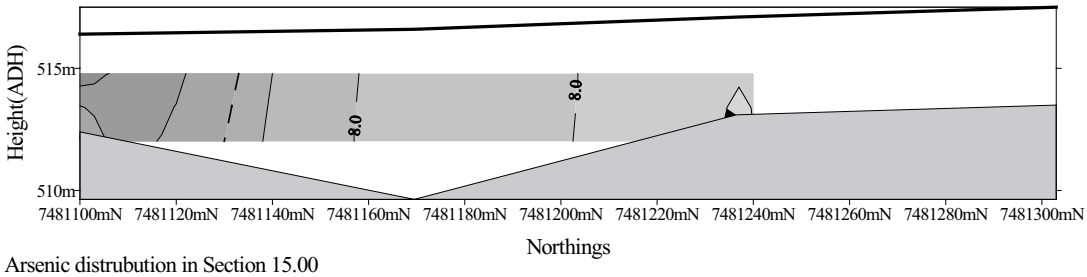
IRON DISTRIBUTION IN THE SECTIONS



Arsenic distrubution in Section 13.95



Arsenic distrubution in Section 14.45



Arsenic distrubution in Section 15.00

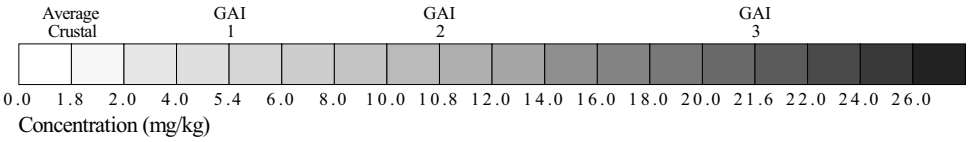
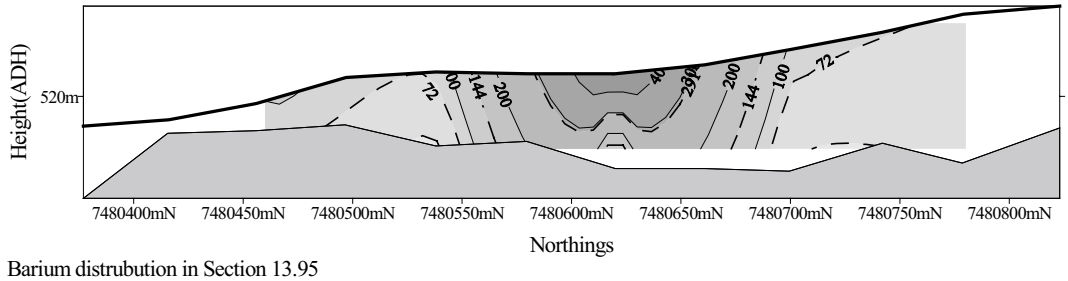
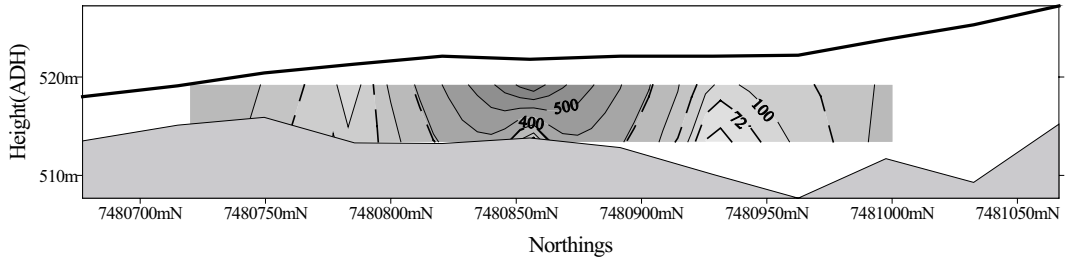


Figure 4.4

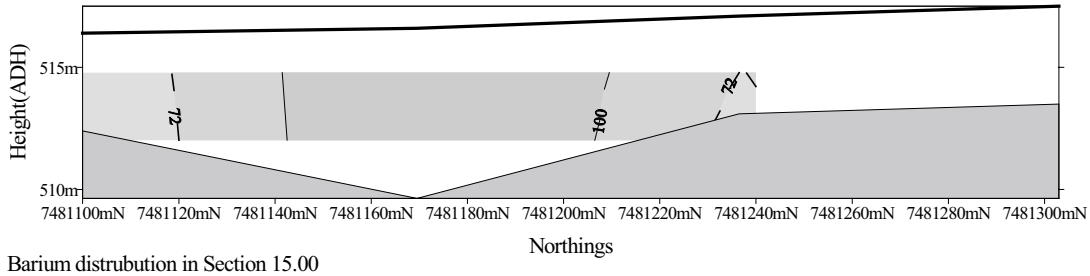
ARSENIC DISTRIBUTION IN THE SECTIONS



Barium distrubution in Section 13.95



Barium distrubution in Section 14.45



Barium distrubution in Section 15.00

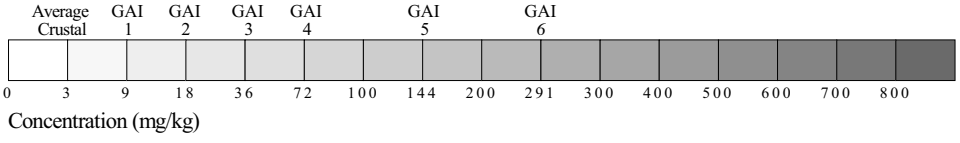
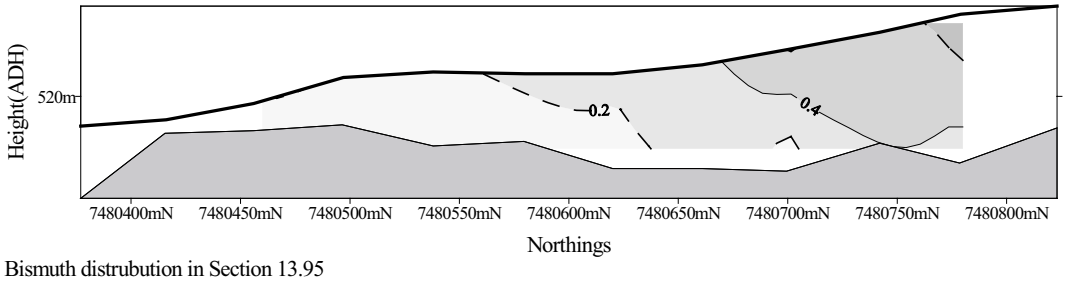
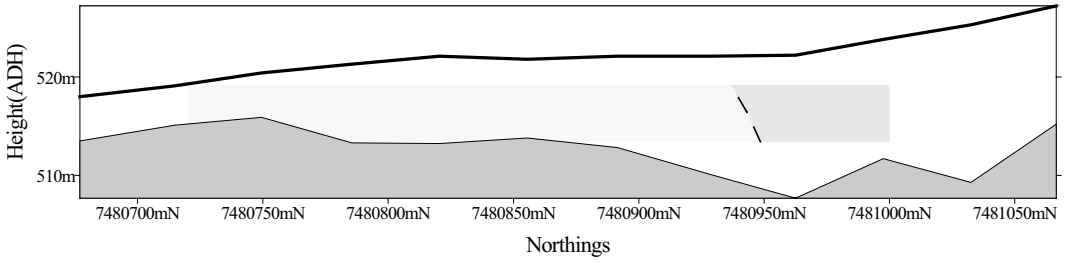


Figure 4.5

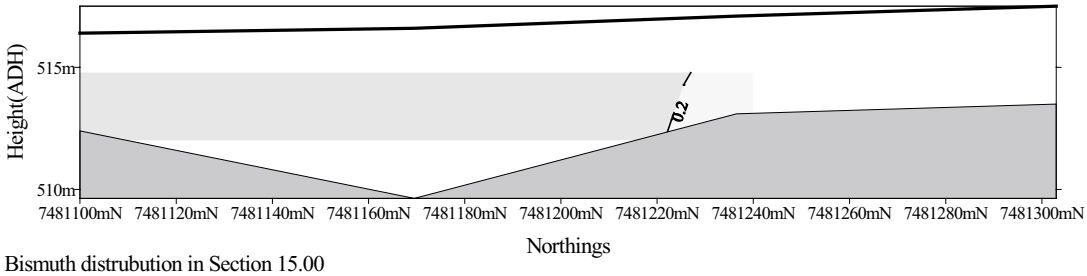
BARIUM DISTRIBUTION IN THE SECTIONS



Bismuth distrubution in Section 13.95



Bismuth distrubution in Section 14.45



Bismuth distrubution in Section 15.00

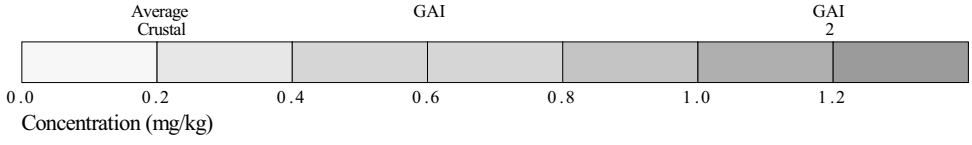
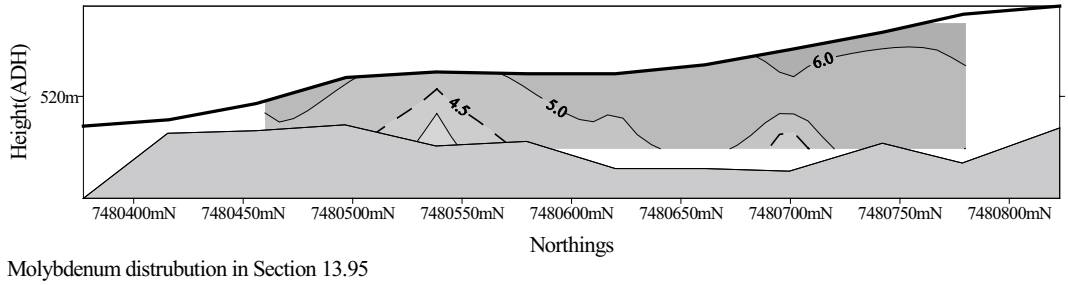
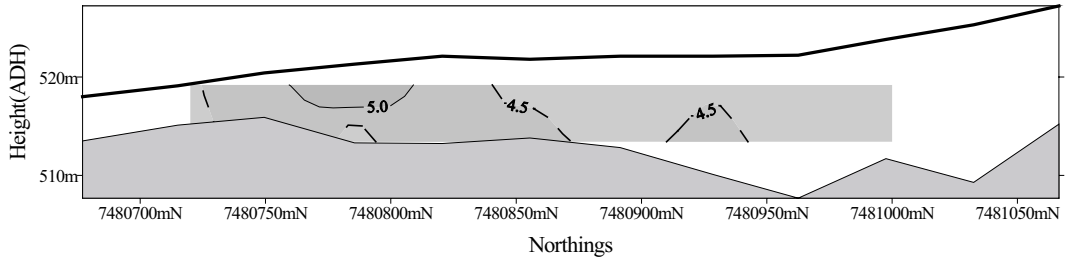


Figure 4.6

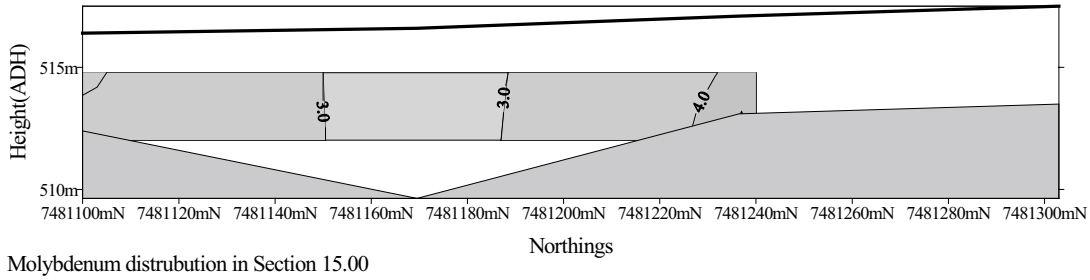
BISMUTH DISTRIBUTION IN THE SECTIONS



Molybdenum distrubution in Section 13.95



Molybdenum distrubution in Section 14.45



Molybdenum distrubution in Section 15.00

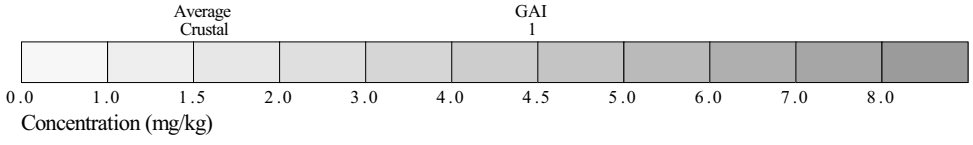
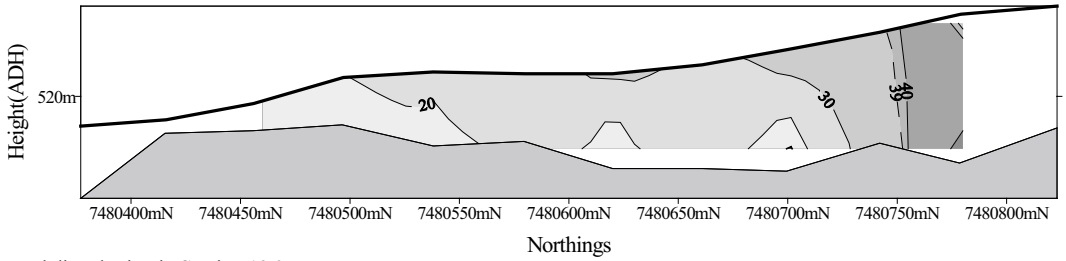
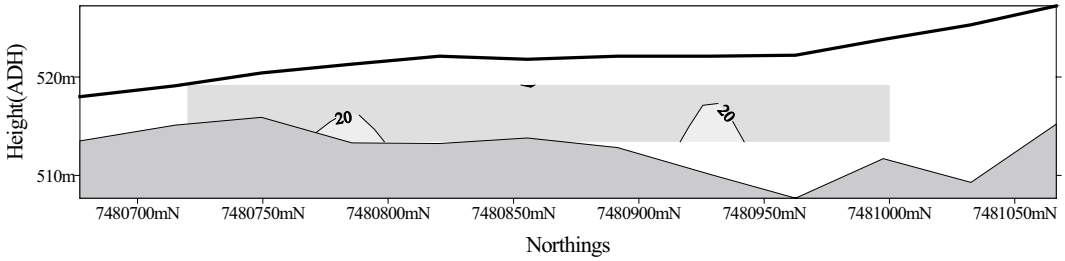


Figure 4.7

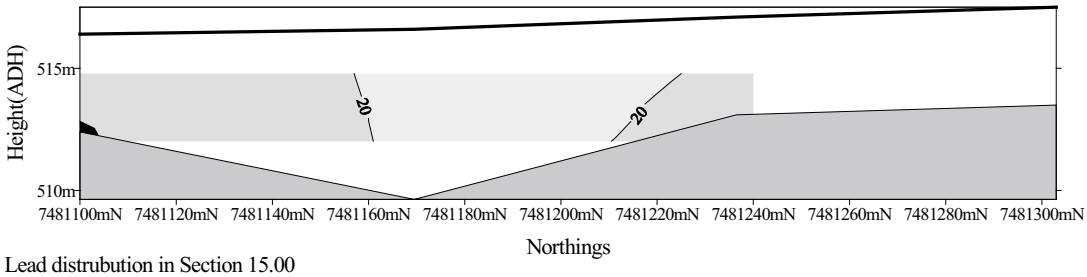
MOLYBDENUM DISTRIBUTION IN THE SECTIONS



Lead distrubution in Section 13.95



Lead distrubution in Section 14.45



Lead distrubution in Section 15.00

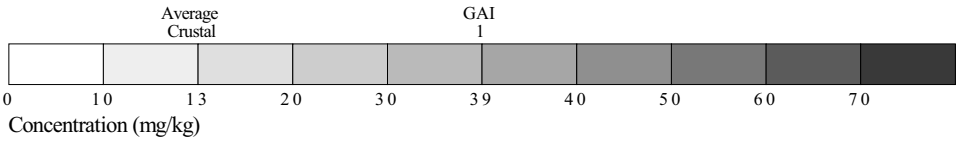
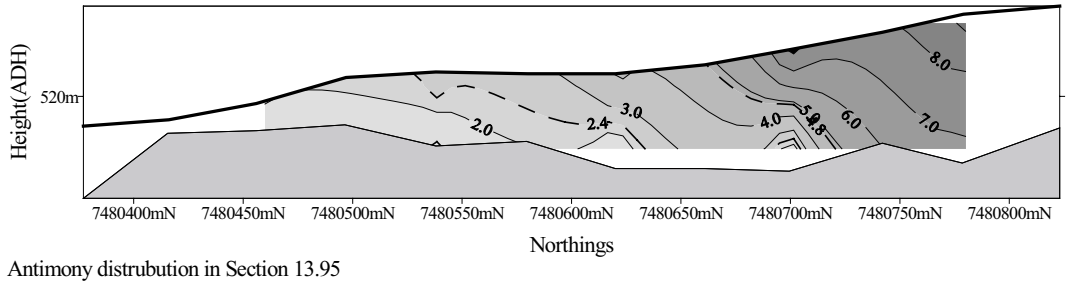
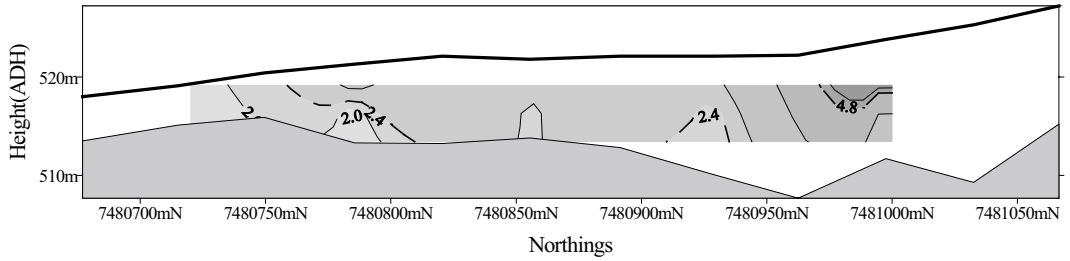


Figure 4.8

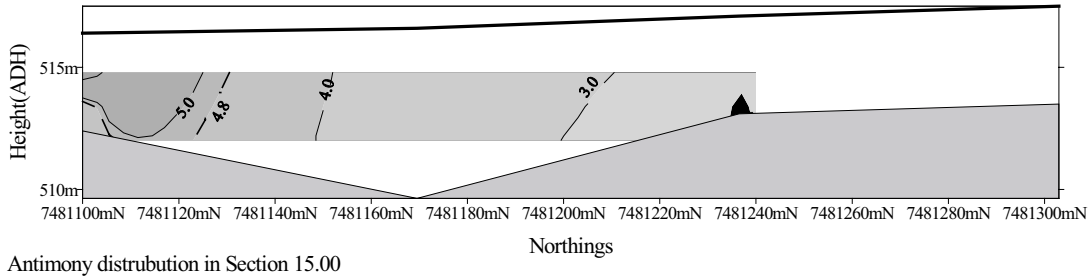
LEAD DISTRIBUTION IN THE SECTIONS



Antimony distrubution in Section 13.95



Antimony distrubution in Section 14.45



Antimony distrubution in Section 15.00

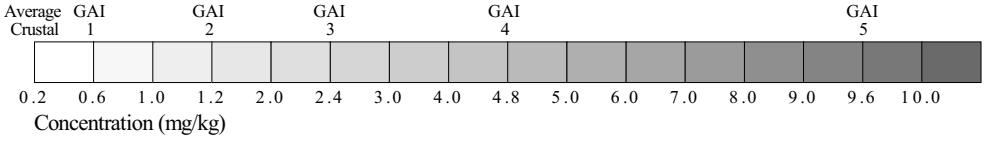
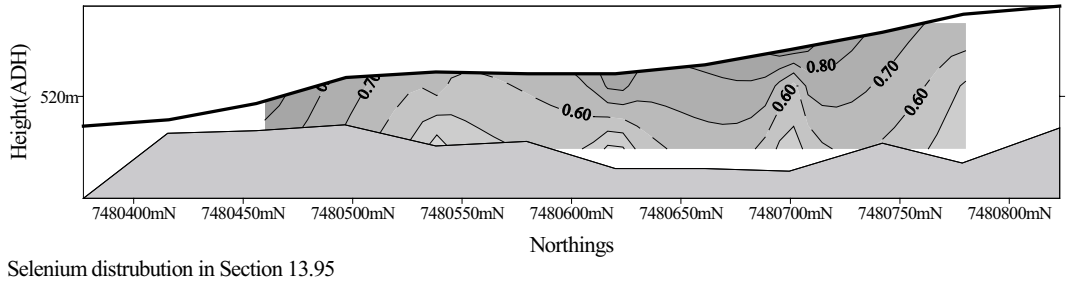
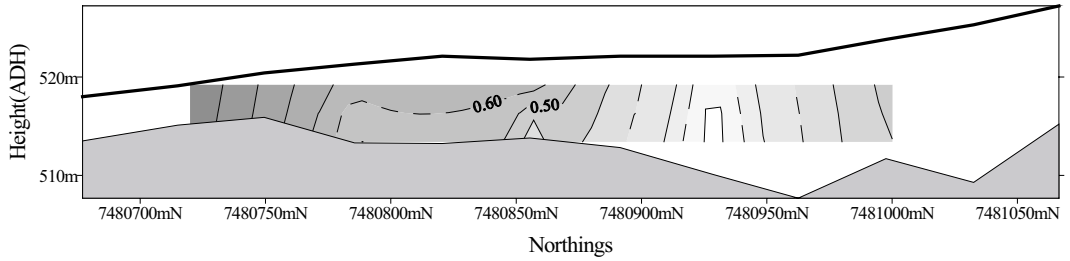


Figure 4.9

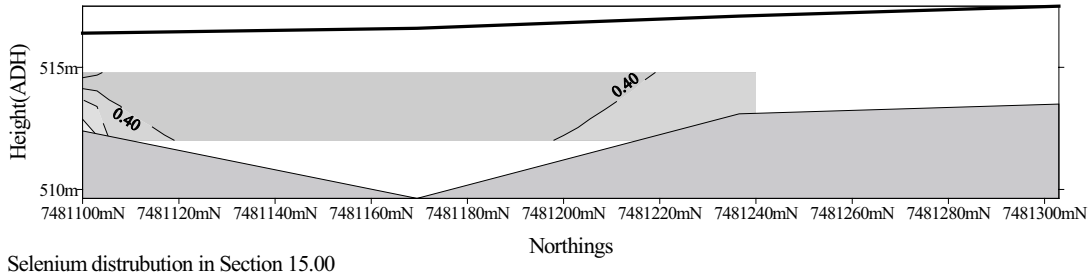
ANTIMONY DISTRIBUTION IN THE SECTIONS



Selenium distrubution in Section 13.95



Selenium distrubution in Section 14.45



Selenium distrubution in Section 15.00

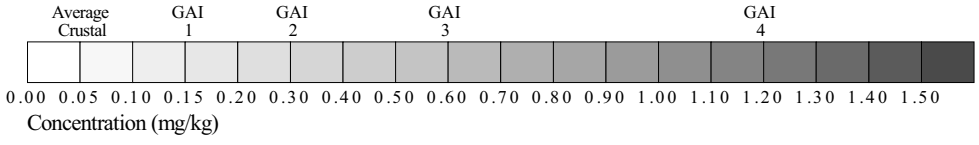
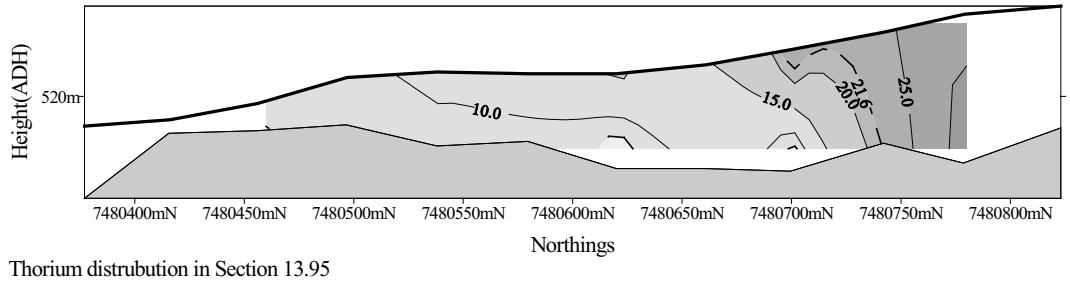
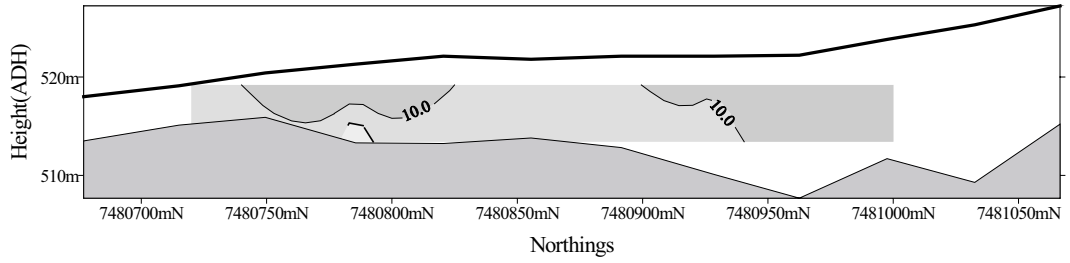


Figure 4.10

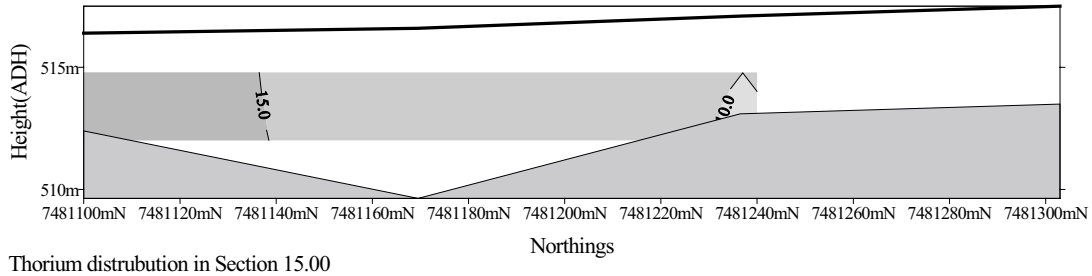
SELENIUM DISTRIBUTION IN THE SECTIONS



Thorium distrubution in Section 13.95



Thorium distrubution in Section 14.45



Thorium distrubution in Section 15.00

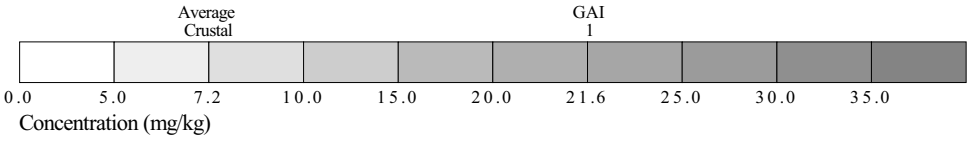
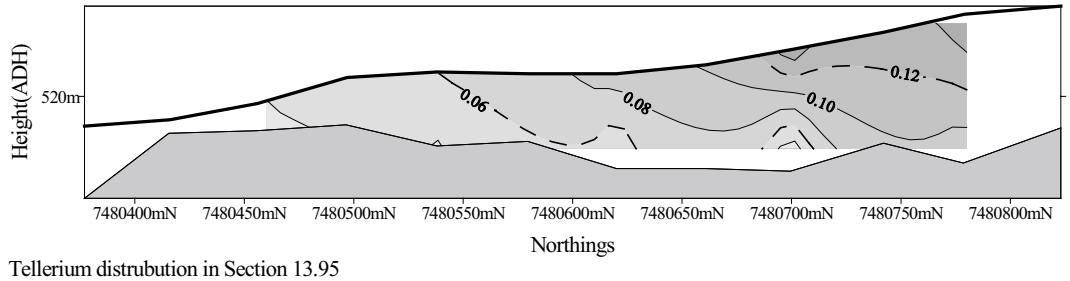
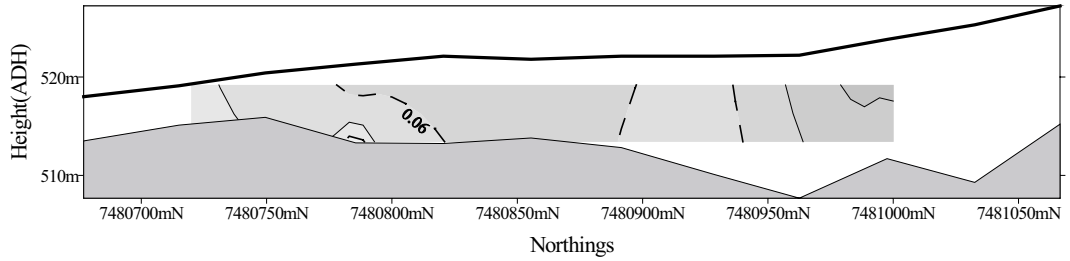


Figure 4.11

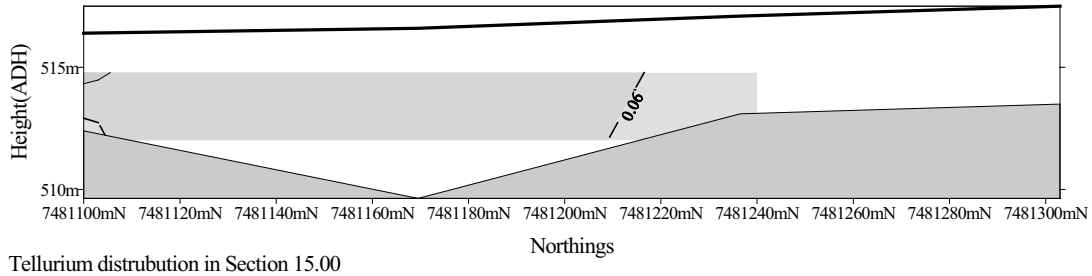
THORIUM DISTRIBUTION IN THE SECTIONS



Tellerium distrubution in Section 13.95



Tellerium distrubution in Section 14.45



Tellurium distrubution in Section 15.00

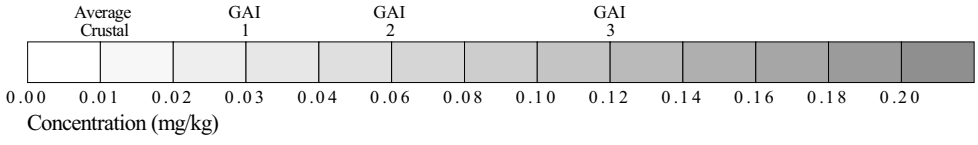


Figure 4.12

TELLURIUM DISTRIBUTION IN THE SECTIONS

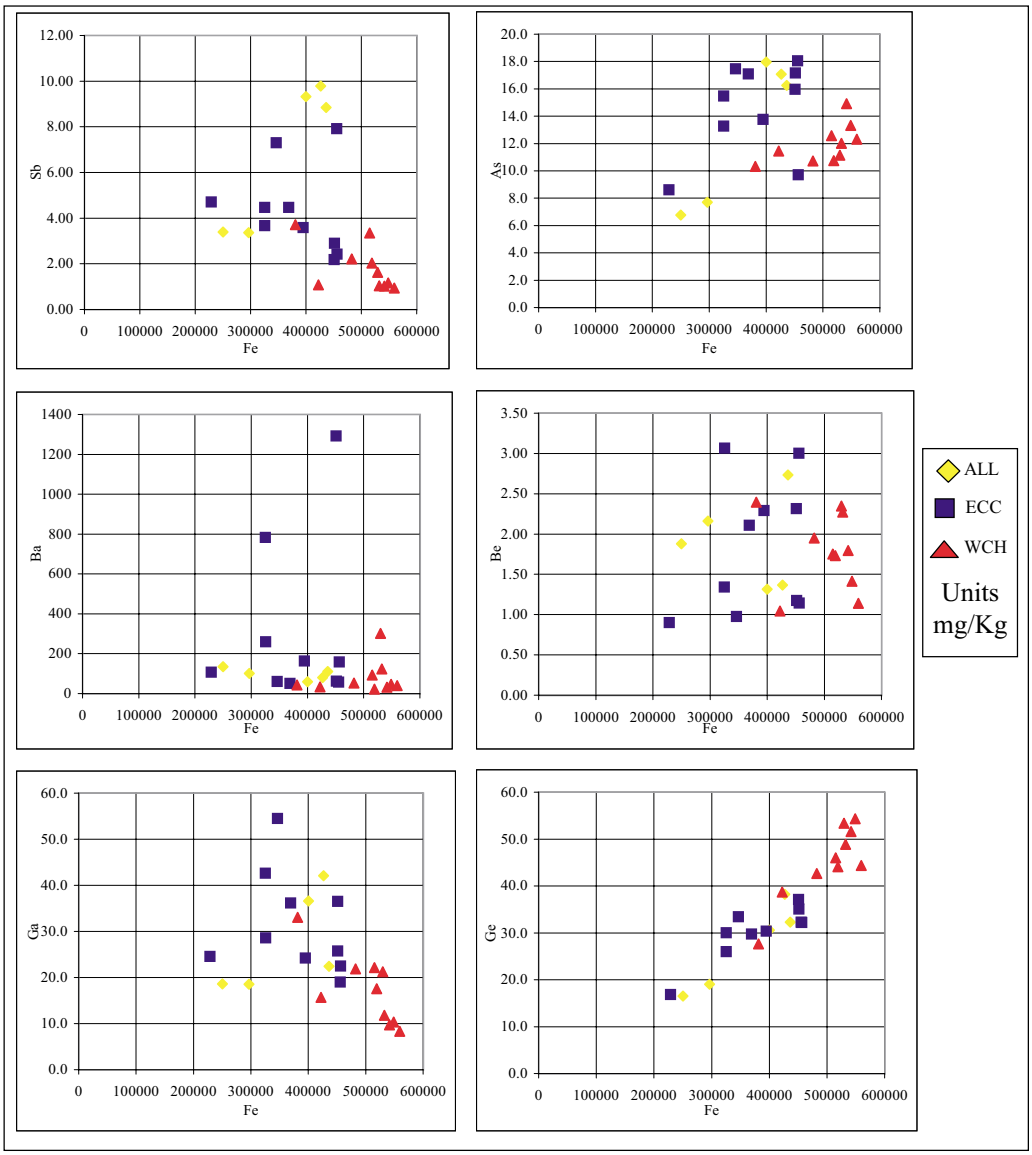


Figure 4.13

IRON CORRELATIONS WITH ROCK SAMPLES

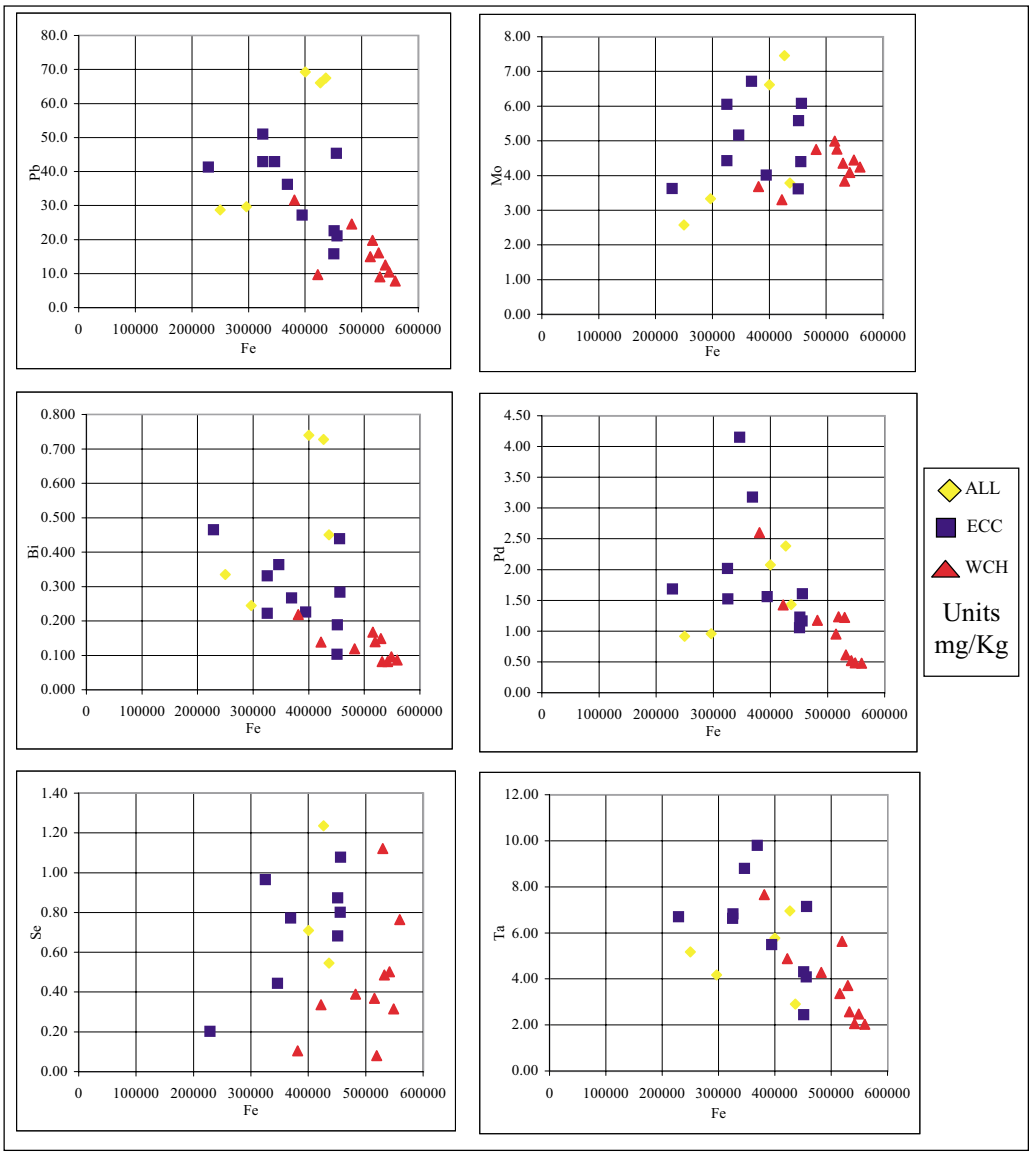


Figure 4.13 (cont.)

IRON CORRELATIONS WITH ROCK SAMPLES

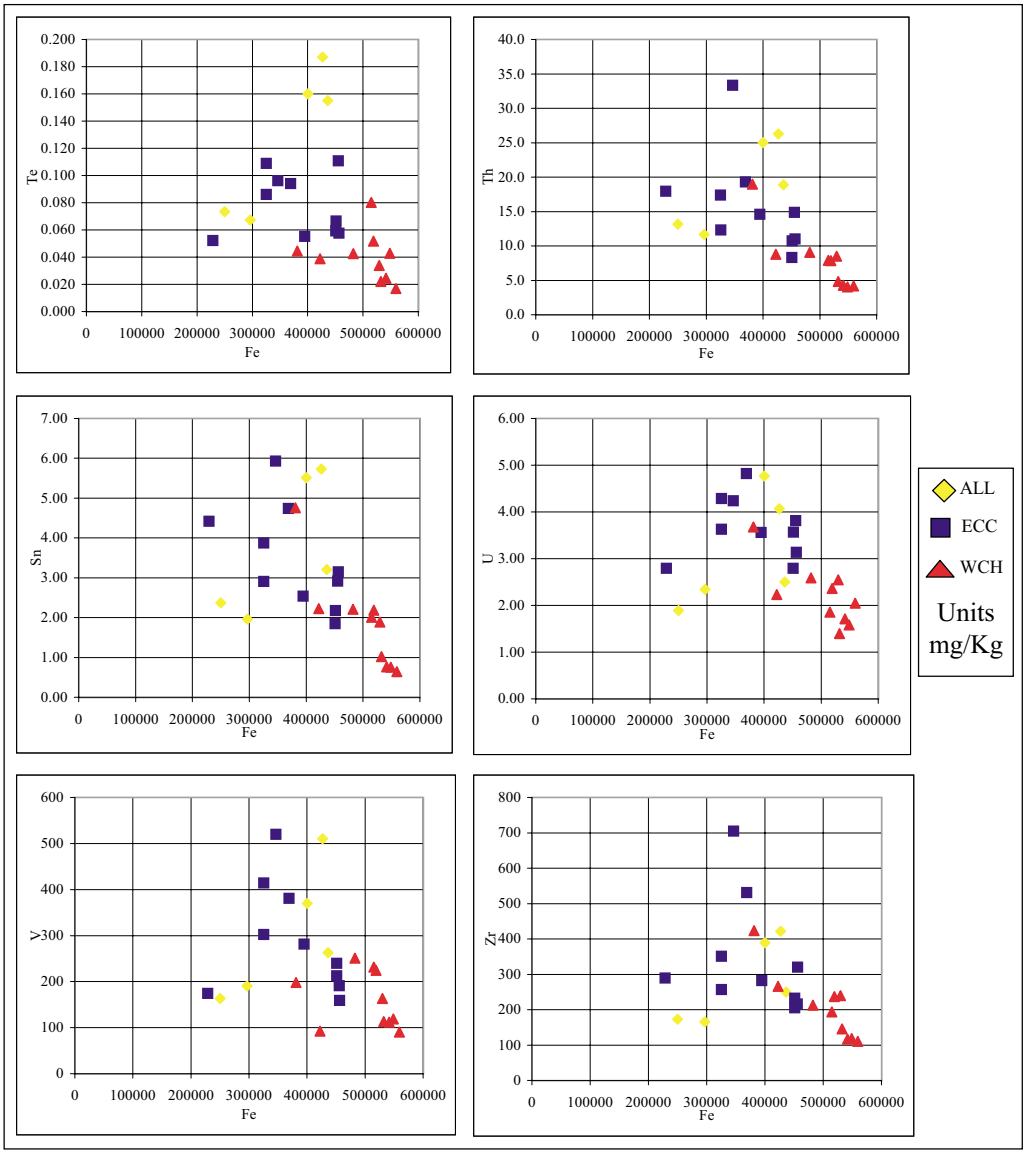


Figure 4.13 (cont.)

IRON CORRELATIONS WITH ROCK SAMPLES

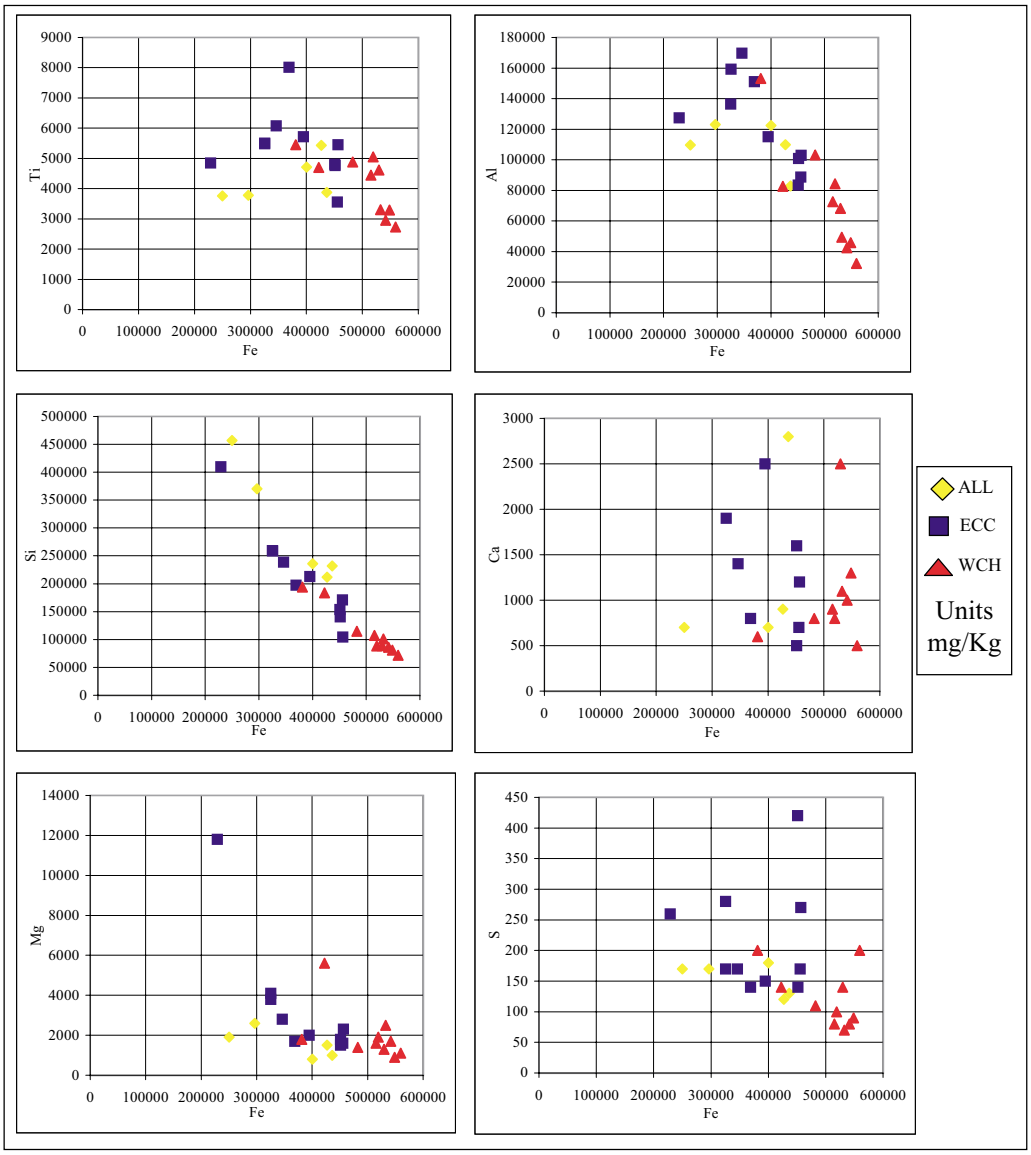


Figure 4.13 (cont.)

IRON CORRELATIONS WITH ROCK SAMPLES

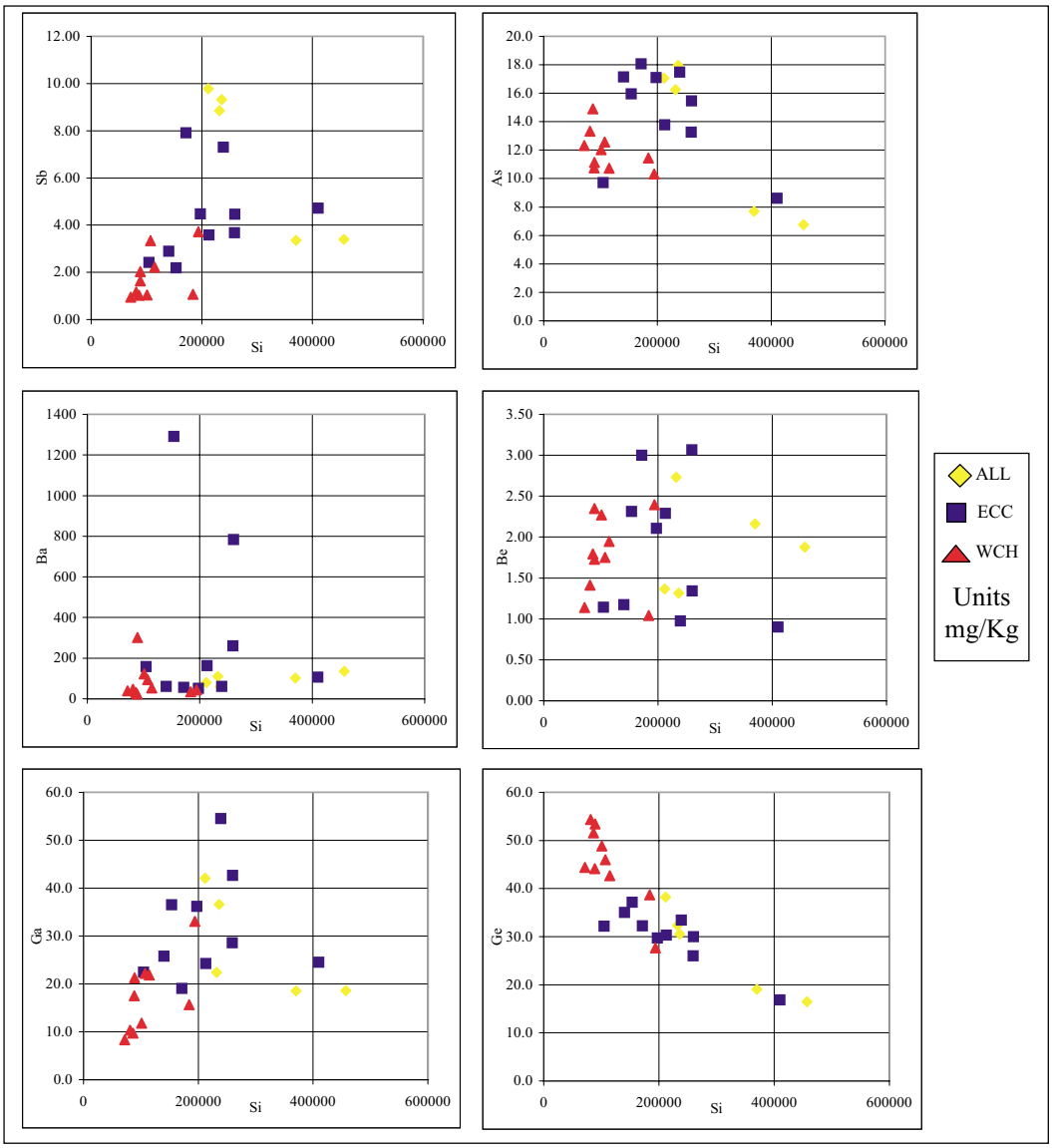


Figure 4.14

SILICA CORRELATIONS WITH ROCK SAMPLES

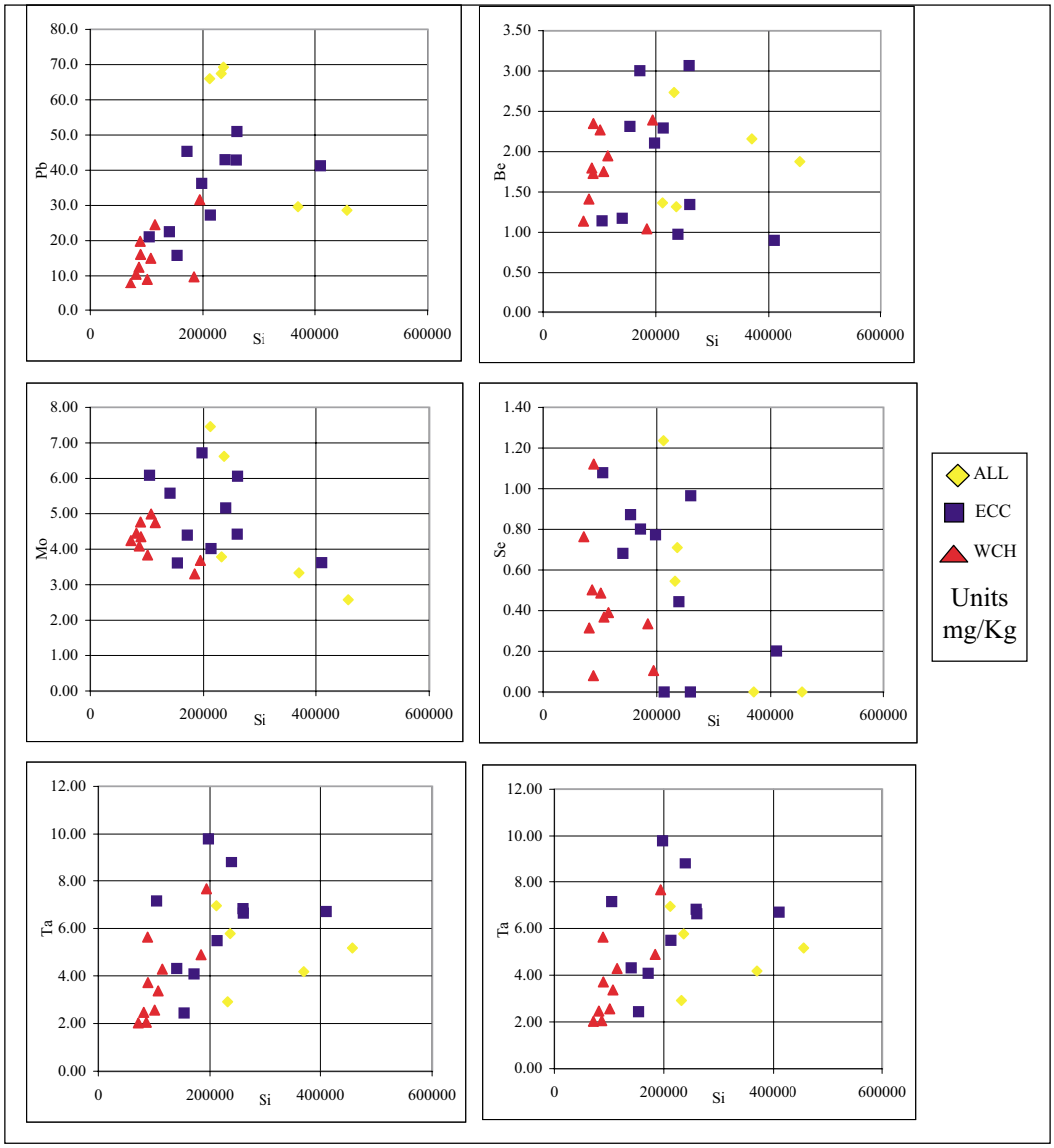


Figure 4.14(cont.)

SILICA CORRELATIONS WITH ROCK SAMPLES

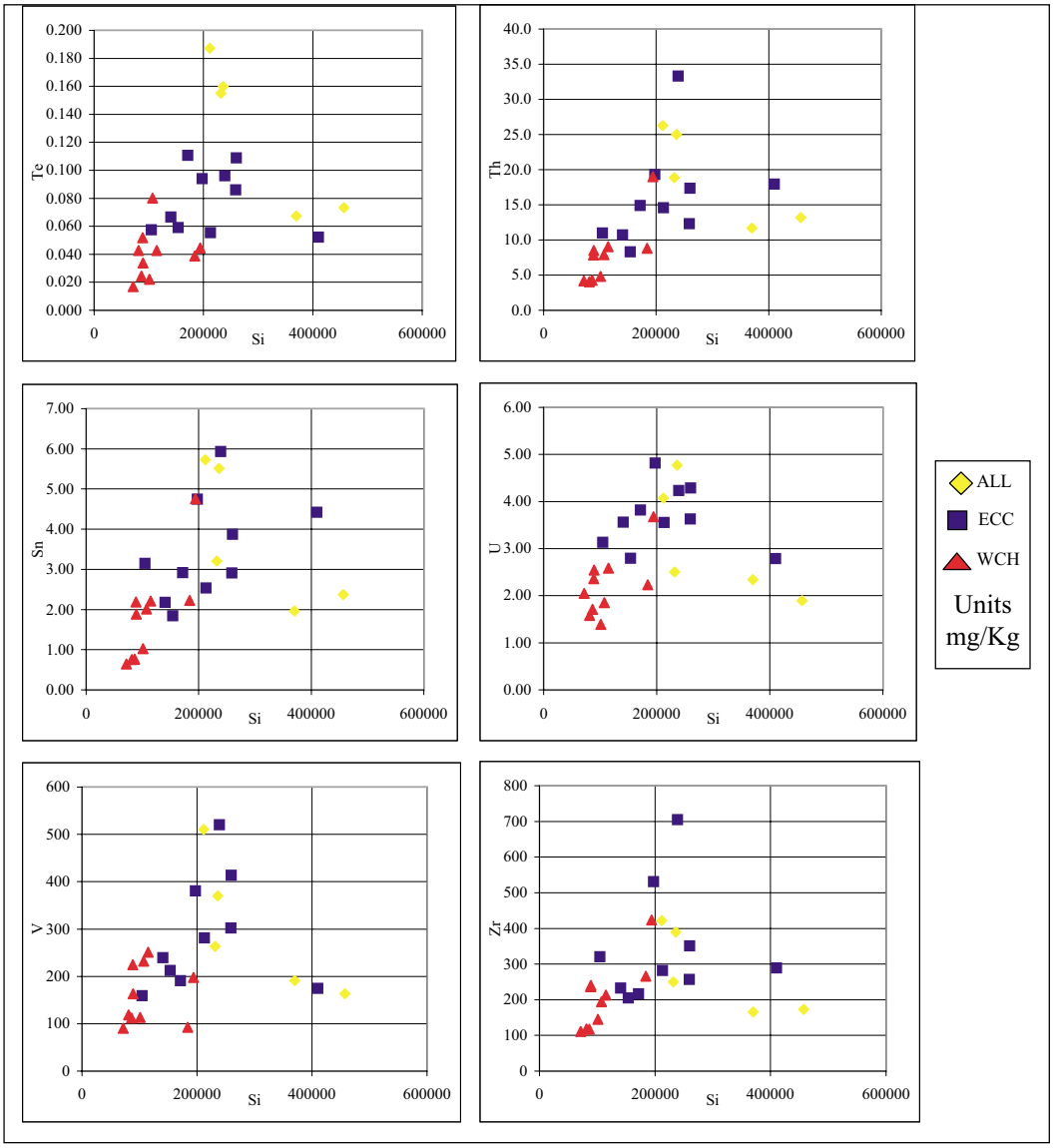


Figure 4.14(cont.)

SILICA CORRELATIONS WITH ROCK SAMPLES

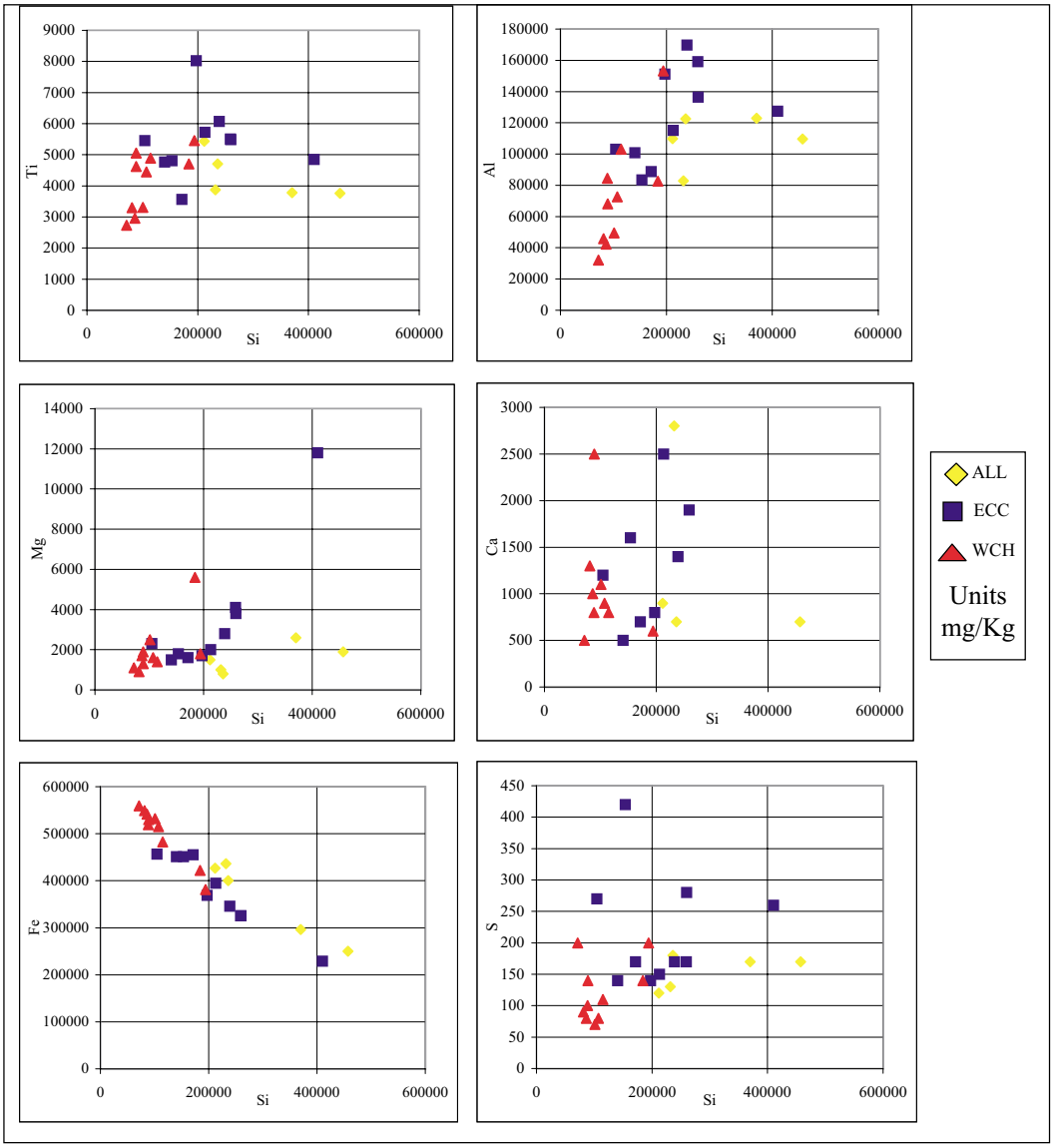


Figure 4.14(cont.)

SILICA CORRELATIONS WITH ROCK SAMPLES

Clay Minerals

Clay minerals are alumina silicates. There are four groups of clay minerals: kandites, illites, smectites and vermiculites. These groups are characterised by the different basal plane spacing of the atoms in the crystal lattice.

Table 4.8 **Shows typical clays.**

Name	Formula
Kaolinite	$Al_4(Si_4O_{10})(OH)_8$
Illite	$K_{1-1.5}Al_4(Si_{7-6.5}Al_{1-1.5}O_{20})(OH)_4$
Montmorillonite	$(0.5Ca,Na)_{0.7}(Al,Mg,Fe)_4((Si,Al)_8O_{20})(OH)_4.nH_2O$
Vermiculite	$(Mg,Ca)_{0.7}(Mg,Fe^{+3},Al)_6(Al,Si)_8O_{20})(OH)_4.8H_2O$

Note Table based on Deer, Howie and Zussman 1966

As well as aluminium and silica clay minerals include other elements such as magnesium, calcium, sodium, potassium, sulphur, iron, manganese, strontium and barium. Clay minerals are usually secondary weathering products of silicate rocks. A very common example is kaolinitised dolerite, that easily breaks down through weathering to kaolinite (Morris *et at,* 1993).

Clay minerals are predominant in both the eastern clay conglomerate and the alluvium. The alluvium has a lower clay mineral content as much of the clay material has been flushed into the underlying eastern clay conglomerate by rainfall over many years.

Several trace elements have strong correlations with the aluminium and silica. Such correlation suggests that the trace elements are associated with these clay minerals. The elements that appear to be associated with the clay minerals are listed below: antimony, bismuth, gallium, lead, palladium, tantalum, tellurium, thorium, tin, vanadium and zirconium.

Iron minerals

These minerals are hydrated iron oxides. The main examples from the CID are goethite, limonite and hematite, although small amounts of siderite and pyrite have been found in the CID (Morris *et al,* 1993).

Table 4.9 **Shows typical iron minerals.**

Name	Formula	Notes
Hematite	Fe_2O_3	common inclusions are silica, aluminium, manganese and titanium.
Goethite	Amorphous FeO.OH	weathering product of hematite.
Limonite	$FeO.OH.nH_2O$	An amorphous or cryptocrystalline weathering product of hematite and goethite.

*Note * Table based on Deer et al 1966*

Rock samples with a greater iron mineral content have higher iron concentration. The correlations in Figure 4.13 show that the trace elements (germanium, molybdenum and selenium) were associated with the iron minerals.

Aluminium, titanium, manganese, vanadium and silica are also incorporated in the lattice of the goethite and hematite minerals as shown in the analyses by Morris *et al* (1993).

Evaporites

These minerals are formed through evaporation of surface and groundwaters. The minerals that may be present are calcite, dolomite halite and gypsum.

Table 4.10 **Shows typical evaporites.**

Name	Formula
Dolomite	$CaMgCO_3$
Calcite	$CaCO_3$
Halite	NaCl
Gypsum	$MgSO_4$

*Note * Table based on Deer et al 1966*

Contamination during preparation

A tungsten carbide Tema mill was used prior to the total digest. This mill contaminated the samples with tungsten. A strong correlation exists between tungsten and mercury. This suggests that the samples were also contaminated with mercury during the preparation. Analyses of acid washed quartz samples are shown in Table 3.10. Due to the strong possibility of contamination during crushing, tungsten and mercury are not further discussed in this study.

Table 4.11 **Shows a summary of the enriched trace elements.**

Element	Concentration range	Average	Average crustal value	Average GAI	Mineral association
Antimony	0.94 – 9.78	3.76	0.2	3	Clays
Arsenic	6.48 – 18.1	13.17	1.8	2	Iron and Clay
Barium	22.8 – 1292	161	3	5	Clay and evaporites
Bismuth	0.08 – 0.74	0.26	0.2	0	Clay
Lead	7.79 – 69.3	29.9	13	0	Clay
Molybdenum	2.43 – 7.46	4.62	1.5	1	Clay and Iron
Selenium	0.08 – 1.24	0.61	0.05	3	Clay and Iron
Tellurium	0.02 – 0.19	0.07	0.01	2	Clay
Thorium	3.75 – 33.3	13.17	7.2	0	Clay

Units mg/kg except GAI which is dimensionless

The results of the correlation analyses suggest that the elements can be grouped to together as listed below.

- Aluminium, cadmium, indium, thorium and titanium
- Silica and thallium
- Iron and germanium
- Lead, bismuth, antimony and tellurium
- Zinc and phosphorus

Possible explanations for some of these correlations are discussed in the following section.

The first two groups are very closely related and primarily associated with alumina silicate clay minerals. However WDS (wavelength dispersive spectrometry) analysis by Morris *et al* (1993), showed that aluminium, silica, vanadium, titanium and manganese are also found as part of the goethite lattice of the peloids cortex (Figure 4.16).

The distribution of these elements will be controlled by the alumina silicates and the peloids.

Iron and germanium have a strong correlation and are found at high concentrations close to the ore body. This suggests that they both can be found together within hematite.

Sulphide minerals occurring in low concentration may explain the correlations between the elements commonly found in sulphides such as lead, bismuth, antimony and tellurium.

4.3 MINERALOGY WITH RESPECT TO ROCK CHEMISTRY

4.3.1 PISOLITE ORE

Morris *et al* (1993) investigated the major chemical distribution within the pisolite ore. WDS was used to map thin sections of the pisolite ore. Samples were studied from several CID from the Hamersley province including Robe River and the Yandi mine. Figure 4.16 shows the distribution of aluminium, silica and iron in a pisolite sample. A selection of the observations from this work is listed below.

Nucleus

The Yandi samples have large spheroids and simple cores compared with other CIDs such as Robe. The nuclei are predominantly iron and have a low aluminium content. The Yandi nuclei had very low levels of aluminium (0.2 % to 0.7 % Al_2O_3).

Cortex

The goethite rim of the peloids has a higher aluminium and silica concentration than the nucleus. In the Yandi samples the rim was up to three times greater than the nucleus. This can vary significantly from spheroid to spheroid.

Matrix

The matrix of the pisolite is generally lower in aluminium and silica than the cortex, but higher than the nuclei. However kaolinite and other alumina rich do make up some areas of the pisolite matrix.

Peloids

The peloids aluminium, silica and iron distributions were similar to the associated nuclei.

4.3.2 CLAYS

Three samples were sent to Graham Horsley of the Chemistry Centre (WA) to identify the clay types using XRPD (X-ray powder diffraction). He identified various types of clay. The analyses showed the presence of smectite, kaolin (that may include kaolinite and dehydrated halloysite), quartz, microcline and possibly trace amounts of anatase. The XRPD spectra of the sample are shown in Figure 4.15.

Table 4.12 **Showing the average mineralogy of the three sections.**

	Alluvium	Eastern clay conglomerate	Weathered channel horizon
Colour	Light Brown	Yellow Brown	Red Brown
B.I.F. (%)	25	Trace	-
B.I.F. (Hematite) (%)	-	Trace	-
Clay (%)	20	10	10
Goethite (%)	0	10	25
Goethite - Limonite (%)	-	5	-
Goethite - Vitreous (%)	Trace	5	45
Hematite - Goethite (%)	25	20	5
Hematite - Ochrous (%)	-	-	Trace
Hematite - Siliceous (%)	10	Trace	Trace
Laterite (%)	-	30	Trace
Limonite (%)	-	Trace	Trace
Limonitic (%)	-	-	Trace
Pisolite (%)	Trace	Trace	Trace
Soil (%)	10	5	Trace

Note observations logged from cores. - Mineral not observed, hematite was generally underestimated and goethite was generally overestimated.

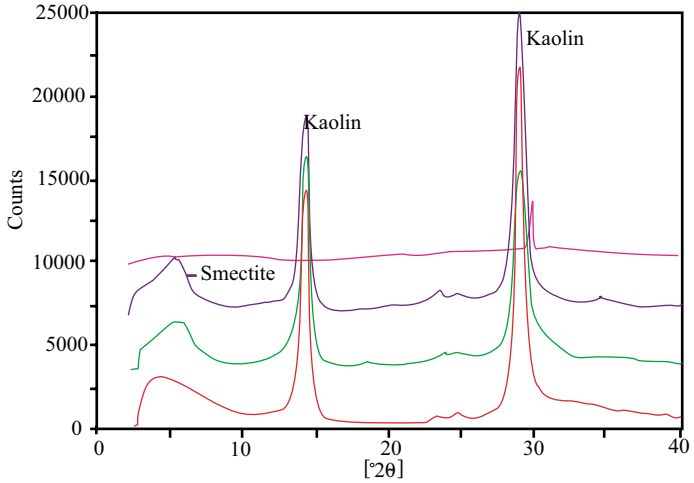
The smectite (montmorillonite) clays are known to be swelling clays that take up significant amounts of water into their structure.

In sodium rich waters montmorillonite may swell 10-20 times its dry volume. In waters with high concentrations of sodium chloride this swelling is suppressed.

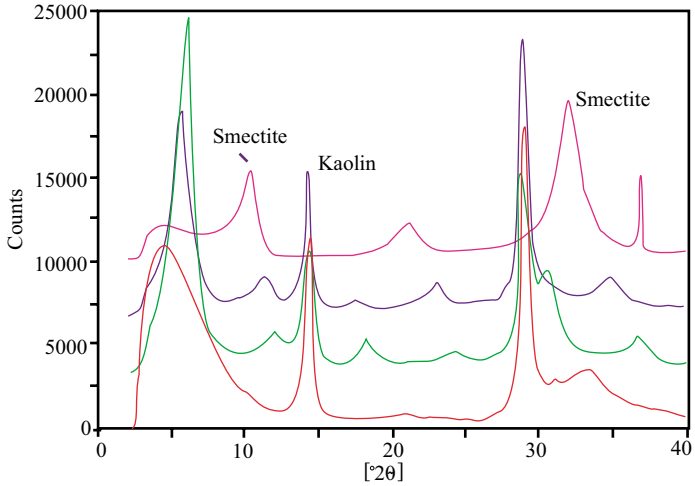
During laboratory experiments the clay swelled. When sodium chloride rich waters were introduced cracks appeared in the clay. This may be due to the clay swelling, then shrinking.

These observations are shown in Figure 4.21. If these cracks were to occur in the channel, they may increase the permeability.

If clays make up a significant proportion of the backfilled waste, the swelling of the clays could impair the hydraulic conductivity. However, if the sodium chloride concentrations were high, the hydraulic conductivity may be increased.

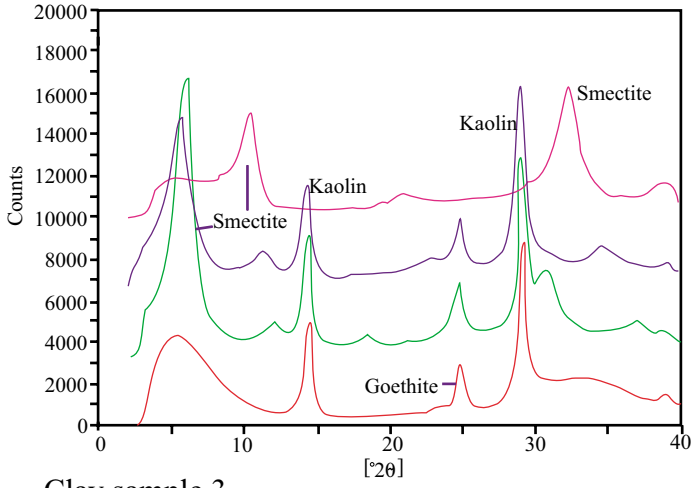


Clay sample 1



Air dried (red)
Na saturated + E/Glycol (Green)
Mg substitudes + Glycerol (Blue)
Air dried - Ignited (Magenta)

Clay sample 2



Clay sample 3

Figure 4.15

XRPD SECTRA FOR CLAY SAMPLES

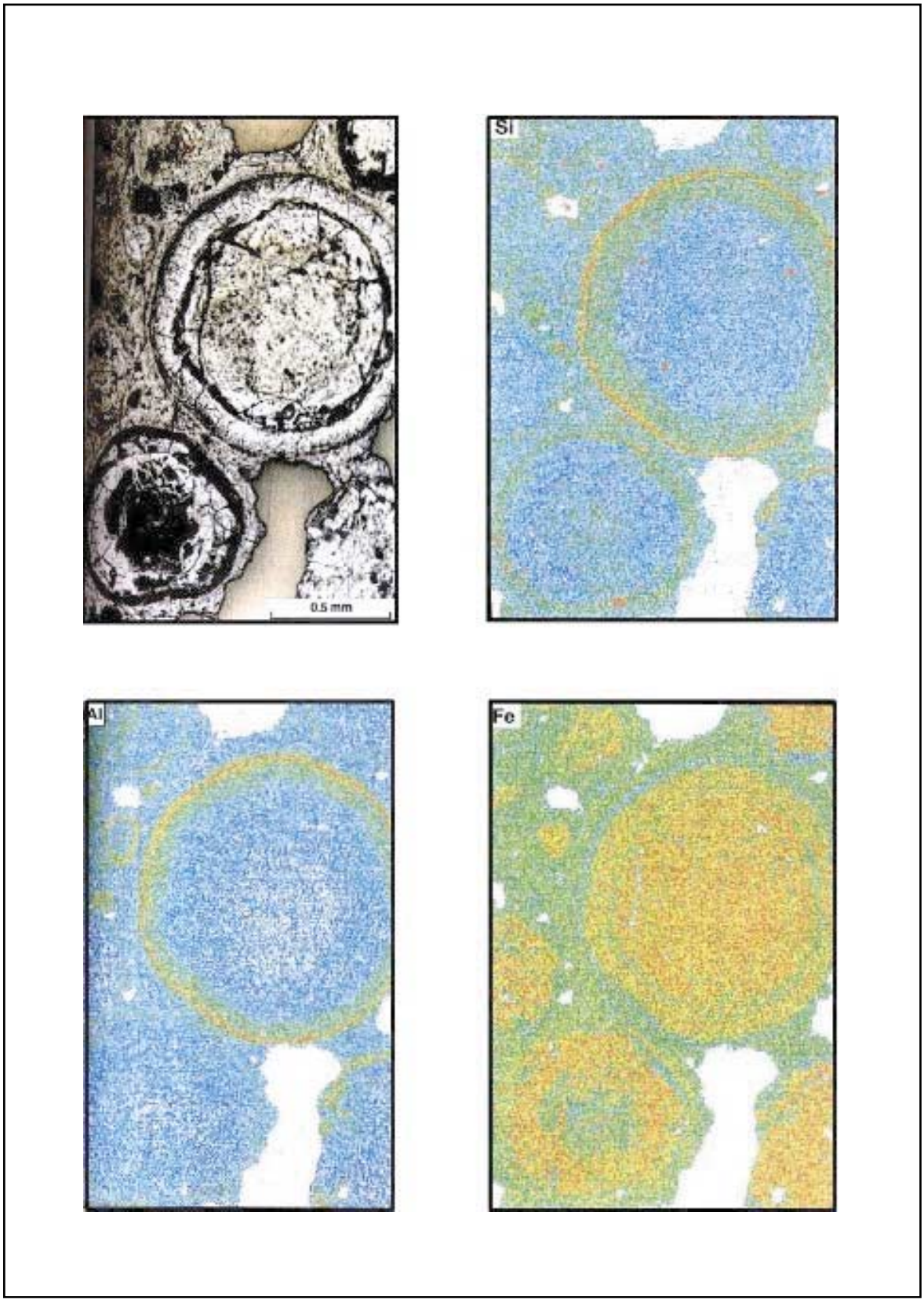


Figure 4.16
WDS X-RAY MAP OF FE, AL AND SI

4.5 WATER QUALITY

The ground and surface waters can be divided into three categories, they are alluvium waters, CID groundwaters and the basement groundwaters. Each has different characteristics that are controlled primarily by the lithologies with which they are associated. Iron concentrations were found to be very low, this is due the relatively high pH of the water due to the high alkalinity.

4.5.1 ALLUVIUM WATERS

The alluvium waters are shallow groundwaters and surface waters. The chemistry of these waters is controlled by three factors:

- The waters have the close contact with the variety of rock types that make up the alluvium.
- Tributaries and other water sources that feed into the Marillana Creek alluvials.
- Evaporation and mineral precipitation.

The rock types within the alluvium are predominantly dolerite, BIF, shale, calcrete, pisolitic hematite and clays. The waters have a relatively low TDS and the major ions are sodium, magnesium, calcium, bicarbonate and chloride.

The chemistry of the alluvium waters sampled have been plotted on a Piper diagram (Figure A.1 – A.4 in the appendix). They show that the waters are essentially very similar but change slightly as the water moves down the Marillana Creek.

The samples Marillana 1, Marillana 2 and the upstream sample have similar cation chemistry but the chloride, nitrogen and sulphate increase further downstream. The ratios suggest that calcium, magnesium and sodium carbonate minerals may have precipitated. This is further supported by the saturation indices in Table 4.14. The decrease in given laboratory TDS is probably due to an error as the TDS based on the sum of the anions and cations contradicts this. The calculated value indicates evaporation occurred and carbonate minerals were precipitated.

Phil's creek intersects with the Marillana Creek after the upstream bore. The Camp sample shows a slight decrease in TDS and increases in calcium and magnesium. This indicates that Phils Creek has a lower TDS but has high concentrations of calcium, magnesium and alkalinity. At Marillana 3 the TDS increases, and there is a relative increase in potassium and a decrease in calcium, sulphate and bicarbonate ions. Inverse calculations later in this section suggest this is due to a mixture of evaporation, dissolution and precipitation of various minerals.

Marillana 4 and 5 samples were taken downstream of the junction of Yandicoogina and Marillana Creeks. These waters have a significantly higher TDS, indicating that the Yandicoogina Creek has a higher TDS and calcium concentration but lower in other cations, alkalinity and sulphate.

The sample taken from the discharge lagoon and Marillana 6 is similar to Marillana 1. This shows there is little change in the pumped water from its source.

Table 4.13 **Equivalent ratios in alluvium waters**

Sample	Na:Cl	K:Cl	Mg;Cl	Ca:Cl	HCO_3:Cl	SO_4:Cl	Na:HCO_3	K:HCO_3	Mg:HCO_3	Ca:HCO_3	Mg:SO_4	Ca:SO_4
Marillana1	1.07	0.054	0.94	0.653	0.380	0.24	2.8	0.14	2.48	1.72	3.95	2.74
Marillana2	1.00	0.047	0.86	0.566	0.329	0.24	3.0	0.14	2.60	1.72	3.55	2.35
Upstream	0.91	0.039	0.75	0.500	0.291	0.25	3.1	0.13	2.60	1.72	3.00	1.98
Campsite	1.03	0.047	0.82	0.660	0.329	0.26	3.1	0.14	2.48	2.01	3.13	2.53
Marillana3	0.97	0.057	0.77	0.456	0.260	0.21	3.7	0.22	2.95	1.75	3.59	2.14
Marillana4	0.59	0.032	0.66	0.449	0.190	0.14	3.1	0.17	3.48	2.36	4.66	3.16
Marillana5	0.82	0.043	0.79	0.593	0.291	0.23	2.8	0.15	2.72	2.04	3.50	2.63
Discharge	0.99	0.060	1.02	0.781	0.412	0.29	2.4	0.15	2.48	1.90	3.53	2.70
Marillana6	1.13	0.071	1.02	0.831	0.494	0.32	2.3	0.14	2.07	1.68	3.14	2.56
Seawater	0.85	0.019	0.21	0.038	0.004	0.10	196.2	4.29	47.71	8.79	1.98	0.36

Note ratio values are dimensionless.

Table 4.14 **Saturation indices for alluvium waters**

Sample	Calcite	Aragonite	Dolomite	Magnesite	Gypsum	Chalcedony	Cristobalite	Leonhardite	Quartz	$ZnSiO_3$
Marillana1	0.53	0.39	1.30	0.29	-1.85	0.08	0.13	20.92	0.54	2.56
Marillana2	0.33	0.19	0.93	0.11	-1.79	0.08	0.13	20.88	0.54	2.34
Upstream	0.06	-0.08	0.38	-0.16	-1.82	0.08	0.13	20.80	0.54	1.96
Campsite	0.06	-0.08	0.31	-0.24	-1.95	0.08	0.13	20.92	0.54	1.89
Marillana3	0.34	0.20	0.99	0.16	-1.89	0.08	0.13	20.88	0.54	2.35
Marillana4	0.05	-0.09	0.36	-0.18	-1.85	0.08	0.13	20.93	0.54	1.59
Marillana5	0.30	0.16	0.81	0.02	-1.80	0.08	0.13	21.03	0.54	2.36
Discharge	0.10	-0.04	0.40	-0.19	-1.80	0.08	0.13	20.92	0.54	1.98
Marillana6	0.02	-0.12	0.21	-0.29	-1.90	0.08	0.13	20.83	0.54	1.98
Modelling allowing minerals to precipitation										
Marillana1	-0.14	-0.28	ppt	-0.34	-1.87	-0.46	-0.41	ppt	ppt	ppt
Marillana2	-0.17	-0.31	ppt	-0.32	-1.80	-0.46	-0.41	ppt	ppt	ppt
Upstream	-0.14	-0.28	ppt	-0.35	-1.84	-0.46	-0.41	ppt	ppt	ppt
Campsite	-0.09	-0.23	ppt	-0.39	-1.93	-0.46	-0.41	ppt	ppt	ppt
Marillana3	-0.13	-0.27	ppt	-0.35	-1.90	-0.46	-0.41	ppt	ppt	ppt
Marillana4	-0.11	-0.25	ppt	-0.38	-1.82	-0.46	-0.41	ppt	ppt	ppt
Marillana5	-0.09	-0.23	ppt	-0.40	-1.82	-0.46	-0.41	ppt	ppt	ppt
Discharge	-0.11	-0.25	ppt	-0.38	-1.91	-0.46	-0.41	ppt	ppt	ppt
Marillana6	-0.09	-0.23	ppt	-0.40	-1.91	-0.46	-0.41	ppt	ppt	ppt

Note positive values indicate saturation, ppt mineral precipitates.

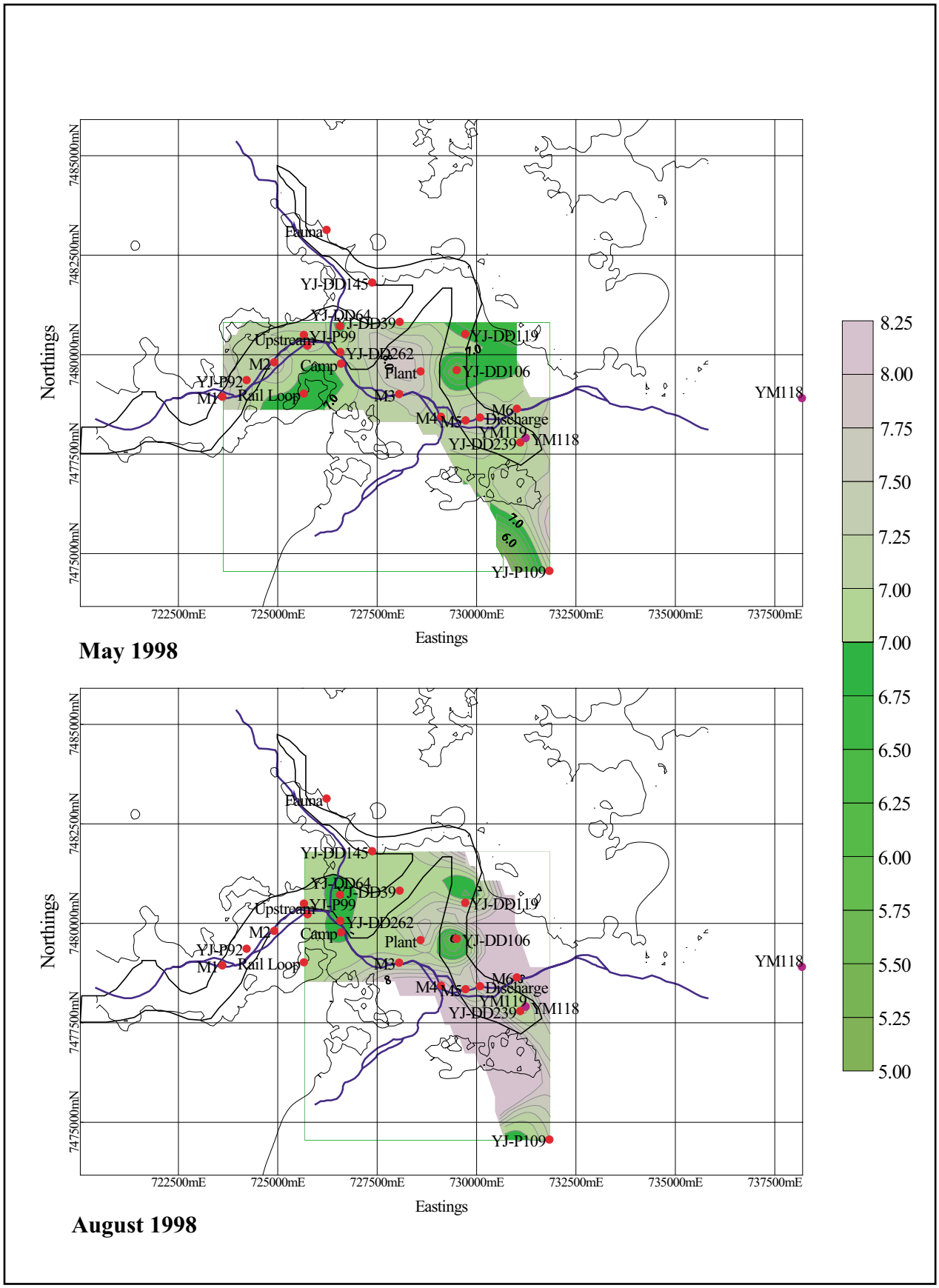


Figure 4.17

THE CHANGE IN THE pH DISTRIBUTION OF THE GROUNDWATER FROM MAY TO AUGUST 1998

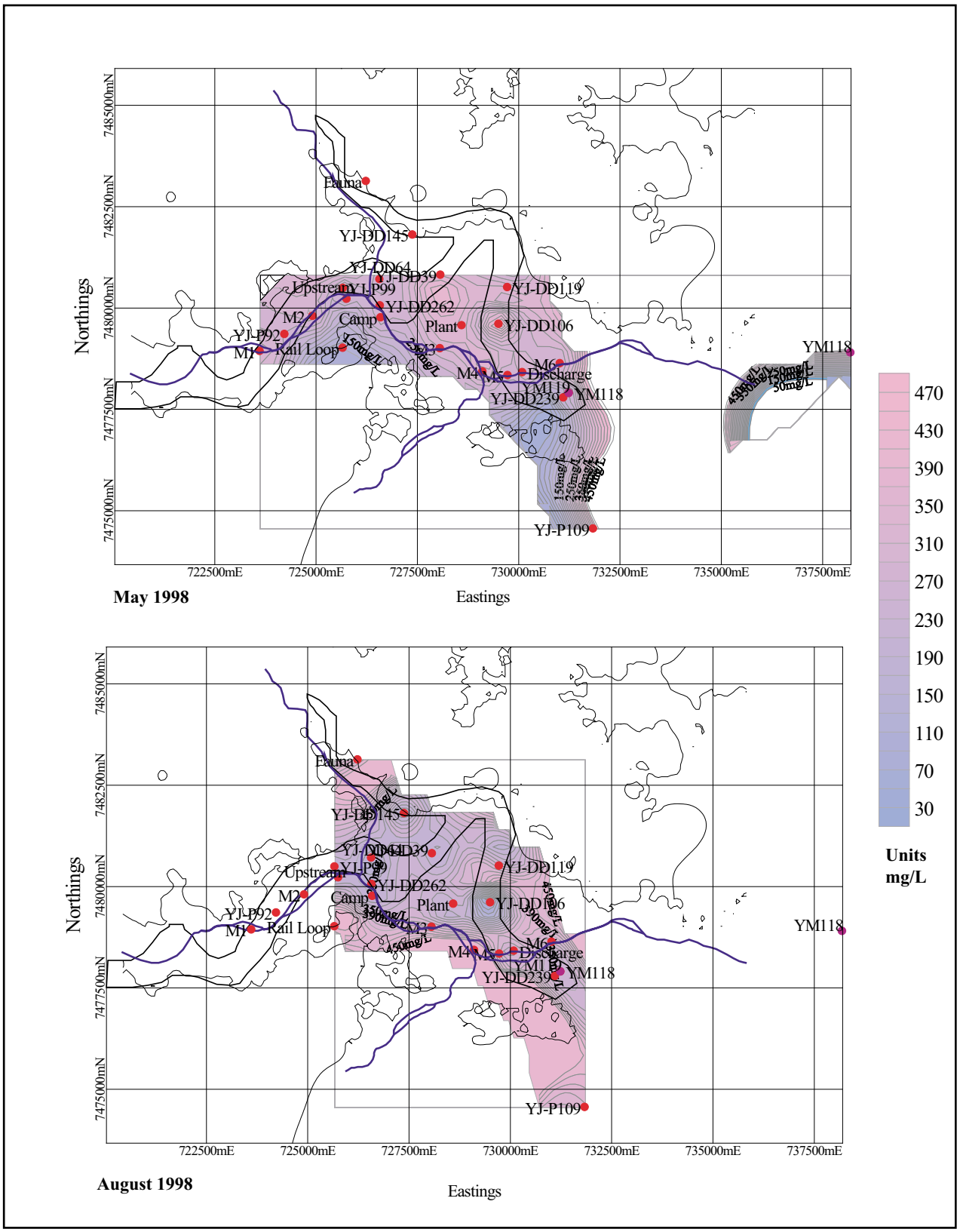


Figure 4.18

THE CHANGE IN THE BICARBONATE DISTRIBUTION OF THE GROUNDWATER FROM MAY TO AUGUST 1998

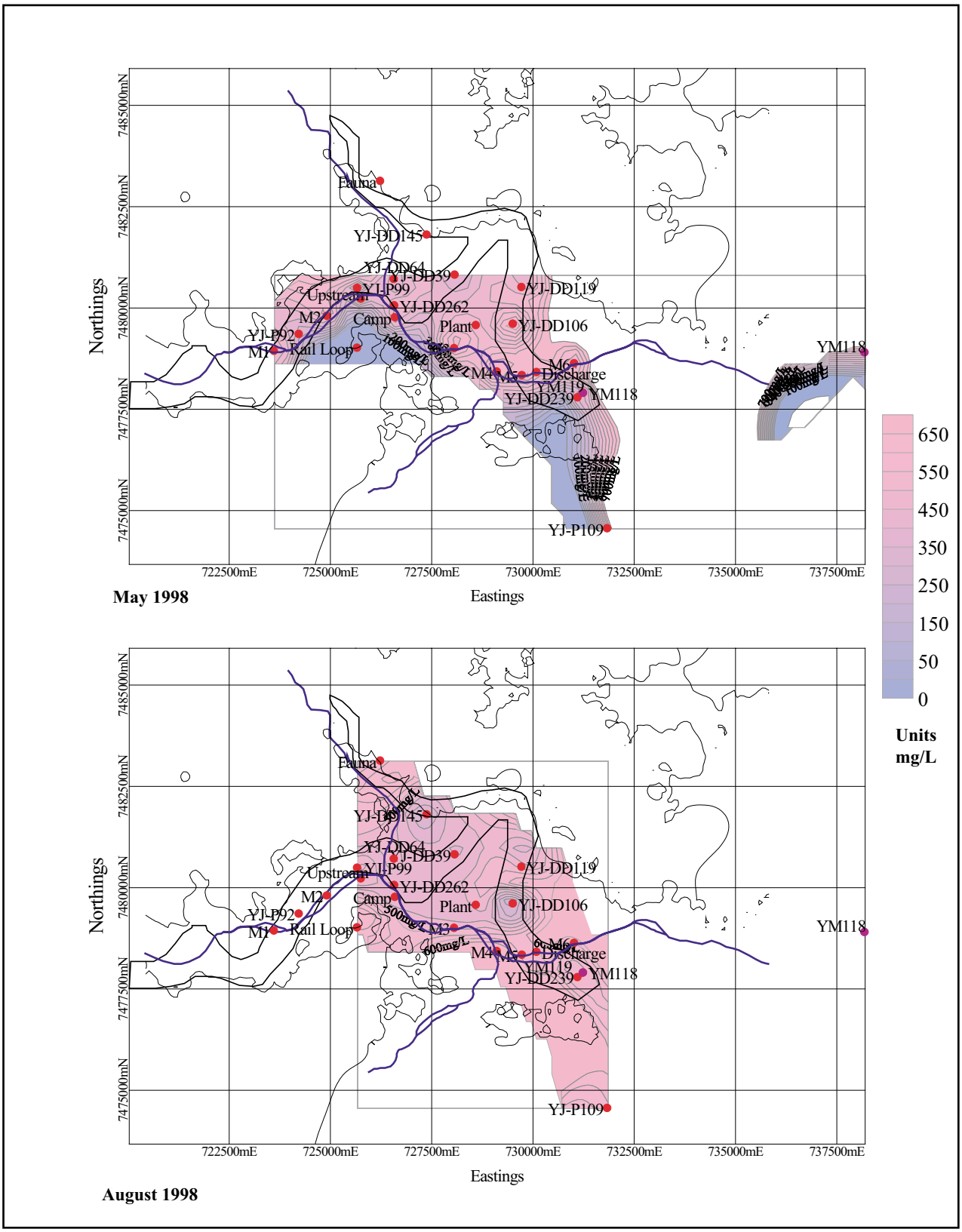


Figure 4.19

THE CHANGE IN THE TDS DISTRIBUTION OF THE GROUNDWATER FROM MAY TO AUGUST 1998

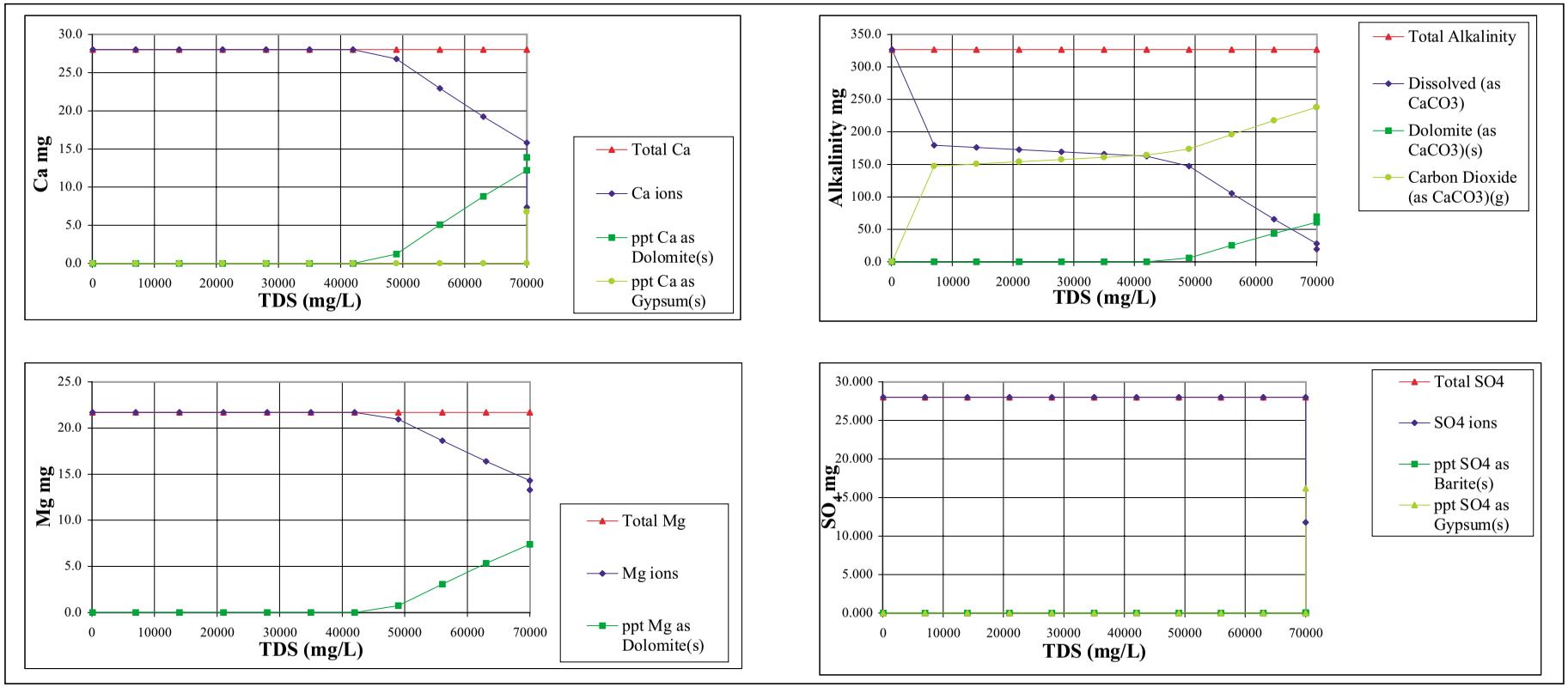


Figure 4.20

SPECIES DISTRIBUTION WITH EVAPORATION

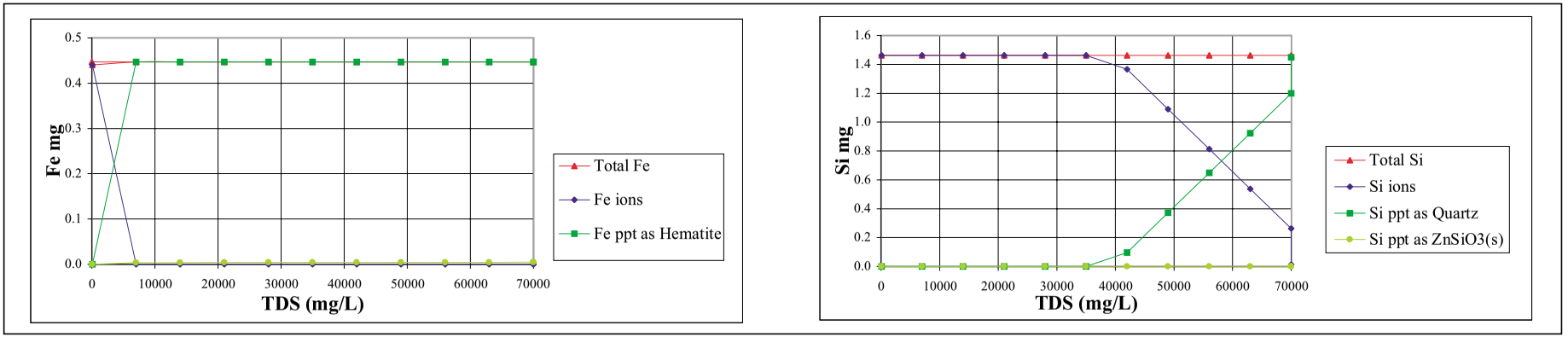


Figure 4.20 (cont.)

SPECIES DISTRIBUTION WITH EVAPORATION

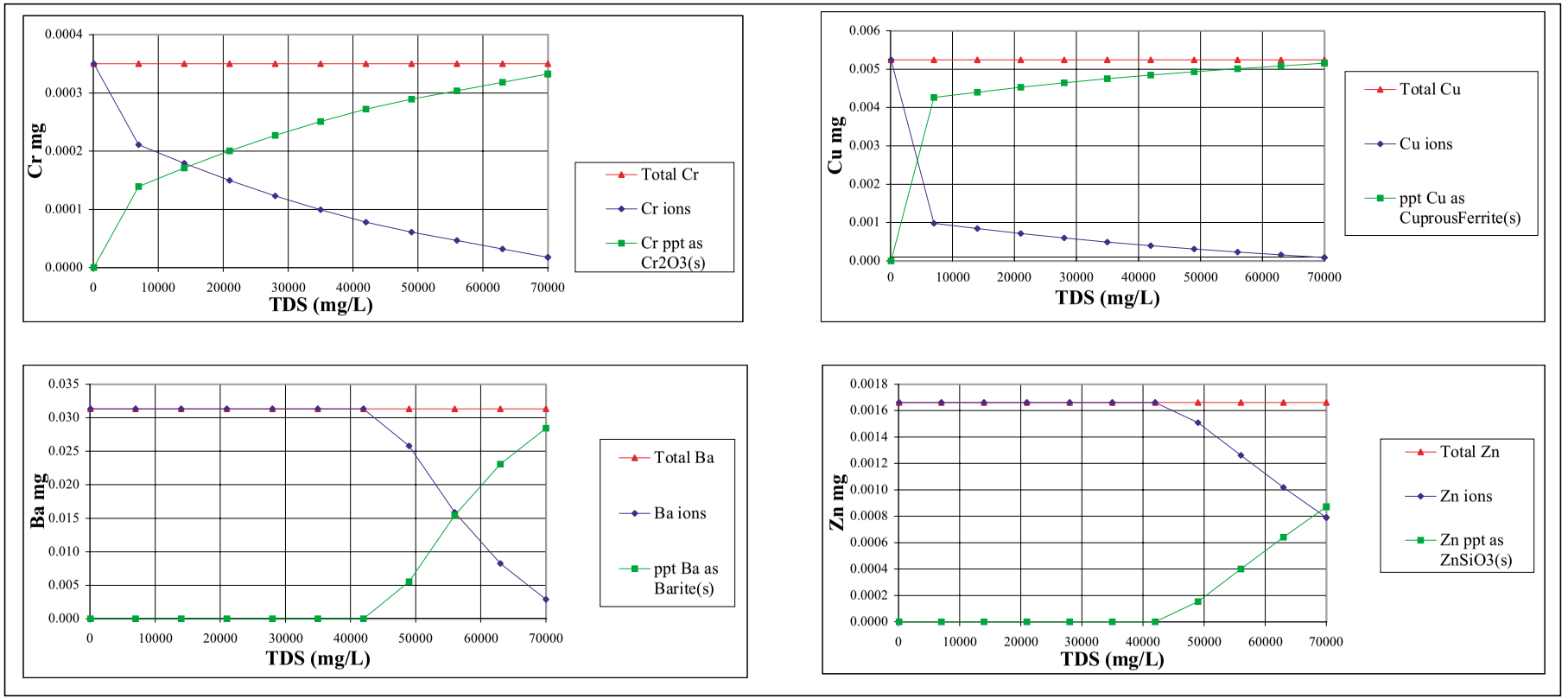


Figure 4.20 (cont.)

SPECIES DISTRIBUTION WITH EVAPORATION

The computer program PHREEQC (Parkhurst, 1995) was used to calculate the saturation indices of minerals likely to change phase in the samples collected. The saturation indices for a selection of minerals are listed in Table 4.14.

The redox potential was not measured during sampling, however these samples were taken at or close to the surface, and therefore positive Eh values were used for the purpose of the geochemical modelling.

The first part of the table shows the saturation indices in the samples if minerals are not allowed to precipitate. This shows a selection of silicate, alumina silicate and carbonate minerals saturated or at near saturation in solution.

The lower part of the table show the same solutions but allowing the minerals to precipitate or redissolve as the saturation index dictates during modelling. The results show that calcium carbonate is likely to precipitate as dolomite, aluminium as leonhardite and silica as quartz and $ZnSiO_3$.

Changes with time

Many of the bores have been sampled on more than one occasion. Studying any changes to the water quality over time may show groundwater trends. Factors that will naturally control the water quality are temperature and rainfall, this will particularly affect the shallow groundwaters.

The most marked difference between the alluvium samples that were taken on the 4th of May 1998 and samples taken a year later (on the 20th April 1999) is that the TDS values were halved. This was probably due to high rainfall diluting the shallow groundwaters.

The seasonal data hydrochemical is limited so it is difficult to drawn any conclusions from this data.

4.5.2 CID WATERS

The waters that move through the CID are in contact with predominantly pisolitic hematite and goethite. These waters have a lower TDS than the alluvium waters. There will be some mixing with the alluvium and basement groundwaters. CID tributaries running beneath Phils and Yandicoogina Creeks will also mix with the Marillana CID groundwaters. The environmental conditions are expected to have a lower redox potential than the alluvium groundwaters, as they are deeper and therefore exposed to less oxygen.

Table 4.15 **Equivalent ratios in CID groundwaters**

Sample	Na:Cl	K:Cl	Mg;Cl	Ca:Cl	HCO_3:Cl	SO4:Cl	Na:HCO_3	K:HCO_3	Mg:HCO_3	Ca:HCO_3	Mg:SO_4	Ca:SO_4
YJP92	-	-	-	-	-	-	-	-	-	-	-	-
YJP99	1.40	0.079	1.41	1.10	2.58	0.46	0.54	0.031	0.54	0.43	3.06	2.40
YJDD64	1.05	0.056	1.08	0.78	1.69	0.34	0.62	0.033	0.64	0.46	3.14	2.28
YJDD262	0.96	0.052	1.04	0.74	1.36	0.28	0.71	0.038	0.77	0.54	3.77	2.66
YJDD39	1.49	0.093	1.79	0.99	2.79	0.34	0.53	0.033	0.64	0.36	5.20	2.89
YJ-DD145	1.23	0.089	0.58	0.24	0.93	0.17	1.33	0.096	0.63	0.25	3.49	1.41
YJDD119	1.39	0.117	1.66	0.85	2.31	0.37	0.60	0.051	0.72	0.37	4.44	2.28
YJDD106	0.96	0.078	0.97	0.69	1.52	0.35	0.63	0.052	0.64	0.46	2.74	1.96
YJDD239	1.08	0.064	1.09	0.77	1.69	0.25	0.63	0.038	0.64	0.46	4.28	3.05
YM118	1.39	0.222	1.31	2.39	3.78	0.55	0.37	0.059	0.35	0.63	2.37	4.31
YM119	1.23	0.166	2.62	1.74	3.97	0.59	0.31	0.042	0.66	0.44	4.45	2.95
YJP109	1.44	0.107	2.02	1.33	3.14	0.46	0.46	0.034	0.65	0.42	4.43	2.91
Seawater	0.85	0.019	0.21	0.038	0.004	0.10	196.2	4.29	47.71	8.79	1.98	0.36

Note ratio values are dimensionless.

The TDS increases slowly as the water moves down the CID. The CID waters contain a higher proportion of alkalinity than the alluvium waters. Dissolved iron is expected to be higher as lower redox conditions favour dissolution of iron minerals that are abundant in the CID.

The individual ion ratios of the samples show that as the TDS increases, so does the chloride value indicating the increase is probably due to evaporation. Only two samples that do not fall into this category are samples YM119 and YJP109, where the increase in TDS seems to be mainly due to the dissolution of carbonate minerals. The graphs in Figure 4.20 show that as the chloride concentration increases, the following ions decrease: calcium, magnesium, alkalinity, sulphate, iron, silica, barium, copper, chromium and zinc. This indicates precipitation of minerals containing these ions and not containing chloride. The minerals that PHREEQC predicted would precipitate are listed in Table 4.16 and include calcite, Mg-nontronite, dolomite and gypsum.

Table 4.16 **Saturation indices for CID groundwaters**

Sample	Calcite	Mg-Nontronite	Dolomite	Gypsum	$Fe(OH)_{2.7}Cl_{0.3}$	Hematite	Pyrite	Sphalerite	Wurtzite	Quartz
YJP99	-1.4	16.9	-2.6	-2.2	2.9	9.5	-56.2	-33.0	-34.9	0.5
YJDD64	-0.8	19.3	-1.4	-2.0	4.0	11.8	-62.2	-36.0	-37.9	0.5
YJDD262	-0.7	19.2	-1.1	-1.9	4.0	11.7	-62.0	-35.2	-37.1	0.5
YJDD39	-0.6	19.6	-0.9	-2.1	4.1	12.1	-63.2	-36.4	-38.3	0.5
YJDD145	-1.3	21.7	-2.1	-2.8	5.0	14.2	-68.8	-	-	0.5
YJDD119	-2.6	11.7	-4.9	-2.5	0.8	4.8	-43.7	-26.3	-28.2	0.5
YJDD106	-0.7	19.4	-1.0	-2.0	4.0	11.9	-62.6	-36.5	-38.4	0.5
YJDD239	-0.7	19.7	-1.1	-2.1	4.1	12.2	-63.4	-37.0	-38.9	0.5
YM118	-0.8	21.7	-1.7	-2.4	4.9	14.2	-68.9	-	-	0.5
YM119	-0.1	21.6	0.1	-1.8	4.9	14.0	-68.3	-	-	0.5
YJP109	-0.1	21.3	0.0	-1.9	4.8	13.7	-67.5	-38.5	-40.4	0.5
Modelling allowing minerals to precipitation										
YJP99	-2.6	-0.3	-4.9	-2.5	-2.4	-1.4	-0.1	-1.4	-3.3	ppt
YJDD64	-1.4	-0.3	-2.6	-2.2	-1.9	ppt	ppt	-0.5	-2.4	ppt
YJDD262	-	0.0	-1.9	-0.4	ppt	ppt	-1.9	ppt	-	-
YJDD39	-1.1	-1.4	-2.0	-1.1	ppt	ppt	-1.9	ppt	-	-
YJDD145	-1.2	-1.8	-2.4	-1.5	-	-	-	ppt	-	-
YJDD119	-0.7	-0.3	-1.0	-2.0	-1.9	ppt	ppt	ppt	-1.9	ppt
YJDD106	-0.7	-0.3	-1.1	-2.1	-1.9	ppt	ppt	ppt	-1.9	ppt
YJDD239	-1.0	-1.1	-1.9	-0.9	ppt	ppt	-1.9	ppt	-	-
YM118	-0.3	0.1	-1.8	-0.3	-	-	-	ppt	-	-
YM119	-	-	-	-	-	-	-	-	-	-
YJP109	-1.5	-2.1	-2.8	-1.3	ppt	-	-	ppt	-	-

Note – indicates that PHREEQC was unable to predict SI of these minerals.

Changes with time

A number of the CID groundwater samples have been sampled on more than one occasion. The results indicate that the chemical composition of these waters changes slightly with the season, although the changes are small and not as marked as in the alluvium samples.

4.5.3 BASEMENT WATERS

The chemistry of the basement waters is controlled by the Weeli Wolli BIF basement rocks and the intruding Dolerite. This has resulted in waters that are relatively high in magnesium, sodium and carbonate. The chloride values are low as the basement waters are deeper and have not undergone concentration by evaporation.

The composition of the waters in this group of samples is highly consistent. The Fauna sample contains more magnesium than the other samples suggesting that the nearby dolerite sill locally contributes magnesium to the groundwater.

Table 4.17 **Equivalent ratios in basement groundwaters**

Sample	Na:Cl	K:Cl	Mg:Cl	Ca:Cl	HCO_3:Cl	SO_4:Cl	Na:HCO_3	K:HCO_3	Mg:HCO_3	Ca:HCO_3	Mg:SO_4	Ca:SO_4
Plant	1.22	0.071	1.04	0.71	1.74	0.32	0.70	0.040	0.59	0.41	3.24	2.21
Rail loop	1.23	0.124	1.87	1.30	2.94	0.38	0.42	0.042	0.64	0.44	4.92	3.42
Rail loop	1.41	0.083	1.24	1.15	2.32	0.41	0.61	0.036	0.53	0.49	3.05	2.83
Fauna	0.93	0.104	2.07	1.03	2.60	0.40	0.36	0.040	0.79	0.40	5.17	2.58
Seawater	0.85	0.019	0.21	0.038	0.004	0.10	196.2	4.29	47.71	8.79	1.98	0.36

Note ratio values are dimensionless.

Table 4.18 **Saturation indices for basement groundwaters**

Sample	Calcite	Aragonite	Dolomite	Gypsum	Hydroxyapatite	Diaspore	$Fe(OH)_{2.7}Cl_{0.3}$	Goethite	Hematite	Magnesite
Fauna	1.3	1.2	3.0	-2.0	6.0	2.0	7.2	7.2	19.4	1.2
Plant	-0.1	-0.3	0.0	-1.9	1.6	3.4	6.5	6.1	17.3	-0.4
Rail loop	0.5	0.4	1.3	-2.0	2.9	2.9	6.7	6.4	17.9	0.3
Fauna	-0.2	-0.4	0.0	-2.1	0.0	0.0	-5.2	-5.5	-6.1	-0.3
Plant	-0.1	-0.2	0.0	-1.9	0.0	0.0	-5.2	-5.6	-6.1	-0.4
Rail loop	-0.2	-0.3	0.0	-2.1	0.0	0.0	-5.1	-5.5	-6.0	-0.3

Note – indicates that PHREEQC was unable to predict SI of these minerals.

4.5.3 INVERSE MODELLING

Inverse modelling was used to estimate changes in the groundwater composition as they travel down the valley. The model provides possible mechanisms to explain the change of chemical composition as the water moves down stream. The model used the initial and final water composition, together with a list of minerals that would have available to dissolve or precipitate.

There is a significant change in chemical composition between the camp and M3 monitoring points. The calcium and sulphate values drop while the TDS, potassium and carbonate increase. From geochemical modelling using PHREEQC, five possible models were produced and are shown below. Each model accounts for the general increase in TDS by evaporation. The changes in the individual ions are predicted to be due to the precipitation or dissolution of dolomite, gypsum, leonhardite, quartz and/or $Al_4(OH)_{10}SO_4$. The models produced were:

- Loss of water by evaporation, dissolution of 18 mg/L of leonhardite providing calcium, aluminium and silica. This solution equilibrates, precipitating various quantities of dolomite, gypsum and quartz.

- Loss of water by evaporation, dissolution of 16 mg/L of leonhardite providing calcium, aluminium and silica. This solution equilibrates, precipitating various quantities of 33.5 mg/L of gypsum and 8.3 mg/L quartz.

- Loss of water by evaporation, dissolution of 11.3 mg/L of leonhardite and 3 mg/L of $Al_4(OH)_{10}SO_4$ providing calcium, aluminium, silica and sulphate. This solution equilibrates, precipitating 33.5mg/L of gypsum and 8.3 mg/L quartz.

- Loss of water by evaporation, dissolution of 7.2 mg/L of leonhardite and 5.7 mg/L of dolomite providing calcium, magnesium, aluminium, silica and alkalinity. This solution equilibrates, precipitating 35.5 mg/L of gypsum.

- Loss of water by evaporation, dissolution of 7.6 mg/L of $Al_4(OH)_{10}SO_4$ providing aluminium and sulphate. This solution equilibrates, precipitating 29.2 mg/L of gypsum.

Table 4.19 **Possible mineral mass exchanges from the campsite to Marillana 3**

Mineral	Formula	1	2	3	4	5
$Al_4(OH)_{10}SO_4$	$Al_4(OH)_{10}SO_4$	-	-	3.0	-	7.6
Dolomite	$CaMg(CO_3)_2$	-9.3	-	-	5.7	-
Gypsum	$CaSO_4{:}2H_2O$	-25.8	-33.5	-31.7	-35.5	-29.2
Leonhardite	$Ca_2Al_4Si_8O_{24}{:}7H_2O$	18.8	16.0	11.3	7.2	-
Quartz	SiO_2	-9.8	-8.3	-5.9	-	-

Note - All values in mg/L

Phils and Yandicoogina Creek water quality has been estimated arithmetically. The calculations assume only mixing of waters has occurred, with no evaporation, dissolution or crystallisation.

The catchment areas were used to calculate the proportion of the solutions used in the mixing calculations. Although these proportions have been adjusted to make the calculations possible.

The mixing proportions used for the camp sample were Phils Creek (15%) and Marillana Creek (85%).

$$\text{Phils Creek} = (\text{camp sample}/0.15) - \frac{(\text{upstream sample} \times 0.85)}{0.15}$$

The mixing proportions used for the Marillana sample were Yandicoogina Creek (30%) and Marillana Creek (70%).

$$\text{Yandicoogina Creek} = (\text{M4 sample}/0.3) - \frac{(\text{M3 sample} \times 0.7)}{0.3}$$

The estimated values for the creeks are shown in Table 4.20.

Table 4.20 **Estimated water quality of the Phils and Yandicoogina Creeks.**

Hydrochemical characteristics	Phils Creek	Yandicoogina Creek
Sodium, Na	100	53
Potassium, K	11	3
Magnesium, Mg	31	80
Calcium, Ca	101	106
Chloride, Cl	37	423
Sulphate, SO_4	25	38
Bicarbonate, HCO_3	233	477
Carbonate, CO_3	<1	<1

Note - All values in mg/L

Phils Creek groundwater is estimated to have very dilute waters, with relatively high concentrations of sodium, potassium, calcium and alkalinity. The Yandicoogina Creek, however is estimated to have groundwater that have undergone evaporation and some precipitation, reducing the concentrations of sodium, potassium, sulphate and alkalinity.

4.6 LEACHATE CHEMISTRY

The solubility of minerals and their elements is dependent on several factors, one of the most important of which is the pH of the solution. Elements will behave

differently under different pH conditions. An example of this is aluminium which is an amphoteric element. It will dissolve easily in acidic and alkaline conditions but is virtually insoluble in neutral conditions.

The rock samples were subjected to leaching experiments to determine which elements would dissolve in the groundwater. The leachate solution varied depending on the samples' composition. The majority of the leachate samples ranged between pH 7.5 and 8.5 due to the buffering of the carbonate minerals to 8.4. The current groundwater pH range is a little lower (pH 5.4 – pH 7.8) which is probably due to the higher dissolved CO_2 concentrations in the groundwater.

The elements that dissolved the most were the major elements, due to their high solubility and abundance. The conditions favoured the dissolution of the anionic elements such as antimony, arsenic, cobalt, chromium, gallium and molybdenum.

The leachates were super saturated with silicate and iron minerals. When super saturated minerals were allowed to precipitate; diaspore, leonhardite, quartz, $ZnSiO_3$ and hematite precipitated. Calcite was also super saturated in some of the samples.

Table 4.21 **Saturation indices for alluvium leachates**

Sample	Calcite	Aragonite	Dolomite	Chalcedony	Cristobalite	Diaspore	Leonhardite	Quartz	$ZnSiO_3$	Hematite
LAET 851	-4.91	-5.05	-10.10	0.22	0.29	3.21	13.94	0.70	0.26	12.82
LAET 861	-4.33	-4.47	-9.04	0.22	0.29	3.43	13.98	0.70	0.41	11.43
LAET 918	0.05	-0.09	-1.00	0.22	0.28	2.72	20.63	0.70	2.10	16.74
LAET 930	-23.40	-23.54	-47.24	0.22	0.29	3.46	13.53	0.70	0.10	13.01
LAET 939	-5.30	-5.44	-10.47	0.22	0.28	3.13	13.88	0.70	2.41	19.24
Modelling allowing minerals to precipitation										
LAET 851	-5.19	-5.32	-10.66	-0.48	-0.42	ppt	-5.36	ppt	-0.86	ppt
LAET 861	-4.35	-4.49	-9.08	-0.48	-0.42	ppt	-5.46	ppt	-0.32	ppt
LAET 918	ppt	-0.14	-1.10	-0.48	-0.42	-0.99	ppt	ppt	ppt	ppt
LAET 930	-	-	-	-0.48	-0.42	ppt	-9.33	ppt	-2.29	ppt
LAET 939	-5.79	-5.92	-11.44	-0.48	-0.42	ppt	-6.01	ppt	ppt	ppt

Table 4.22 **Saturation indices for eastern clay conglomerate leachates**

Sample	Calcite	Aragonite	Dolomite	Chalcedony	Cristobalite	Diaspore	Leonhardite	Quartz	$ZnSiO_3$	Hematite
LAET 827	-3.44	-3.57	-7.15	0.22	0.29	2.80	12.62	0.70	-0.09	11.53
LAET 837	-23.41	-23.55	-46.91	0.22	0.29	3.45	14.58	0.70	1.86	11.13
LAET 841	0.03	-0.11	-1.22	0.22	0.28	2.81	20.80	0.70	2.14	16.67
LAET 853	-1.25	-1.39	-2.19	0.22	0.28	2.52	17.98	0.70	2.61	18.31
LAET 865	-4.83	-4.97	-10.35	0.22	0.29	3.38	13.20	0.70	0.43	12.90
LAET 888	-4.20	-4.34	-8.40	0.22	0.29	3.42	15.22	0.70	0.87	13.47
LAET 898	-0.29	-0.43	-1.50	0.22	0.28	2.69	20.38	0.70	3.24	16.75
LAET 908	-0.43	-0.57	-1.80	0.22	0.28	2.90	20.23	0.70	1.89	18.05
LAET 920	-3.53	-3.67	-7.87	0.22	0.28	3.14	15.93	0.70	1.52	16.66
LAET 932	-23.45	-23.59	-47.16	0.22	0.29	3.24	11.63	0.70	-0.79	9.13
Modelling allowing minerals to precipitation										
LAET 827	-3.50	-3.63	-7.27	-0.48	-0.42	ppt	-4.39	ppt	-0.88	ppt
LAET 837	-	-	-	-0.48	-0.42	ppt	-7.15	ppt	ppt	ppt
LAET 841	ppt	-0.14	-1.28	-0.48	-0.42	-0.96	ppt	ppt	ppt	ppt
LAET 853	-1.19	-1.33	-2.03	-0.48	-0.42	-0.66	ppt	ppt	ppt	ppt
LAET 865	-4.84	-4.98	-10.38	-0.48	-0.42	ppt	-5.99	ppt	-0.30	ppt
LAET 888	-4.18	-4.32	-8.36	-0.48	-0.42	ppt	-4.05	ppt	ppt	ppt
LAET 898	-0.26	-0.40	-1.44	-0.48	-0.42	-1.03	ppt	ppt	ppt	ppt
LAET 908	-0.43	-0.57	-1.79	-0.48	-0.42	-0.76	ppt	ppt	ppt	ppt
LAET 920	-3.45	-3.59	-7.70	-0.48	-0.42	ppt	-1.95	ppt	ppt	ppt
LAET 932	-	-	-	-0.48	-0.42	ppt	-10.12	ppt	-3.07	ppt

Table 4.23 **Saturation indices for weathered channel horizon leachates**

Sample	Calcite	Aragonite	Dolomite	Chalcedony	Cristobalite	Diaspore	Leonhardite	Quartz	$ZnSiO_3$	Hematite
LAET 828	-33.27	-33.41	-66.64	0.22	0.29	3.49	15.22	0.70	-0.19	12.93
LAET 840	0.00	-0.14	-0.44	0.21	0.28	2.36	19.76	0.69	2.52	16.62
LAET 844	-2.52	-2.66	-5.53	0.22	0.29	3.39	17.11	0.70	1.09	17.25
LAET 856	-3.31	-3.45	-7.33	0.22	0.28	3.12	16.13	0.70	1.50	18.71
LAET 878	-0.25	-0.39	-1.70	0.22	0.28	2.94	20.55	0.70	2.12	16.47
LAET 890	-3.72	-3.86	-7.44	0.22	0.28	2.94	16.66	0.70	2.62	20.10
LAET 900	-4.15	-4.29	-8.14	0.22	0.29	3.38	15.14	0.70	1.12	15.86
LAET 910	-3.35	-3.49	-6.49	0.22	0.28	3.03	16.39	0.70	2.51	19.32
LAET 933	-23.32	-23.46	-46.67	0.22	0.29	3.43	13.07	0.70	0.06	10.80
LAET 940	-4.81	-4.95	-9.30	0.22	0.29	3.43	13.95	0.70	0.78	15.57
Modelling allowing minerals to precipitation										
LAET 828	-	-	-	-0.48	-0.42	ppt	-7.19	ppt	-2.29	ppt
LAET 840	ppt	-0.14	-0.42	-0.48	-0.42	-1.20	ppt	ppt	ppt	ppt
LAET 844	-2.60	-2.74	-5.68	-0.48	-0.42	ppt	-2.33	ppt	-0.07	ppt
LAET 856	-3.31	-3.45	-7.34	-0.48	-0.42	ppt	-1.98	ppt	ppt	ppt
LAET 878	-0.24	-0.38	-1.68	-0.48	-0.42	-0.79	ppt	ppt	ppt	ppt
LAET 890	-3.96	-4.10	-7.93	-0.48	-0.42	ppt	-1.66	ppt	ppt	ppt
LAET 900	-4.16	-4.29	-8.15	-0.48	-0.42	ppt	-4.04	ppt	ppt	ppt
LAET 910	-3.39	-3.52	-6.57	-0.48	-0.42	ppt	-1.49	ppt	ppt	ppt
LAET 933	-	-	-	-0.48	-0.42	ppt	-8.92	ppt	-1.96	ppt
LAET 940	-4.84	-4.98	-9.36	-0.48	-0.42	ppt	-5.49	ppt	-0.12	ppt

4.7 FUTURE GROUND WATER QUALITY

Using the results of groundwater analysis and PHREEQC, the future of the groundwater quality resulting from mine closure have been estimated. The evaporation modelling helped to establish if minerals were likely to precipitate during evaporation and provided an estimate of final groundwater quality.

4.7.1 GEOCHEMICAL MODELLING OF EVAPORATION OF LAKE

Three different methods were used to model the evaporation. The first method (Model 1) simply used arithmetic and multiplied the analytical constituent by the same factor that increased the TDS to the predicted final value. The second (Model 2) and third (Model 3) methods used PREEQC to increase the TDS to the final salinity by removing pure water over a 10 steps to simulate evaporation: Model 2 allowed saturated minerals to precipitate, Model 3 did not.

The modelling used assumptions established by Peck (1998) in his hydrogeological modelling. Pecks assumptions include the water would enter the pit lakes from the groundwater in the CID, basal rocks, rainfall on the surface of the lake and run off from the local catchment area. Water would be lost by evaporation and possibly flow into the CID downstream of the void. The evaporation would be controlled by the geometry of the voids.

The model indicated that evaporation would increase lake salinity. Peck (1998) estimated that the final salinity could reach 70,000 mg/L. However, due to mineral precipitation, the salinity is not likely to exceed 42,000 mg/L. Both outcomes were modelled.

The evaporation modelling used groundwater values measured during this study. For simplicity, the model assumed that no new water entered the lake and that the lake was initially empty. Evaporation has a greater effect on water quality than fresh water entering the lake.

Table 4.24 **Evaporation of Existing groundwater**

	Original	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
			Salinity 70000 mg/L			Salinity 42000 mg/L	
Site Name	YJP99	Using TDS	without ppt	with ppt	Using TDS	without ppt	with ppt
EC (Lab)	54	16652					
pH	6.23		5.6	5.6		5.8	5.8
Salinity	227	70000			42000		
TDS	240	74009			44405		
Alkalinity (as $CaCO_3$)			94209	4327		60477	3670
Major ions (mg/L)							
Sodium, Na*	40.9	12612	11794	11879	7567	7571	7664
Potassium, K*	3.9	1216	1125	1133	730	731	731
Calcium, Ca*	28.0	8634	8074	1652	5181	5183	1378
Magnesium, Mg*	21.7	6687	6256	3818	4012	4016	2487
Chloride, Cl	45	13877	12976	13069	8326	8330	8433
Sulphate, SO_4	28	8634	8074	2404	5181	5183	2208
Carbonate, CO_3	<1		2.88	0.13		2.4	0.15
Bicarbonate, HCO_3	200	61674	114931	5279	37004	73778	4477
Nutrients							
Nitrogen (total)	1	308	273	274	185	175	177
Trace elements (µg/L)							
Barium, Ba	31	9660	9000	60	5800	5700	45
Beryllium, Be	0.14	40	40	40	30	26	27
Cadmium, Cd	0.08	20	20	20	10	15	15
Chromium, Cr	0.35	110	100	5	70	65	3.3
Copper, Cu	5.24	1620	1500	20	970	970	16
Iron, Fe			126000	0		81000	0
Lead, Pb	1.73	530	500	500	320	320	320
Nickel, Ni	0.64	200	180	190	120	120	120
Selenium, Se	1.88	580	540	550	350	350	350
Strontium, Sr	67	20670	19000	19500	12000	12000	12500
Thallium, Tl	0.01	0	3	3	2	1.8	1.8
Uranium, U	0.12	40	30	30	20	20	20
Zinc, Zn	1.66	510	500	200	300	300	140

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

The modelling shows that certain elements such as calcium, magnesium, carbonate, sulphate, barium, silica, iron, chromium, copper and zinc are likely to be precipitated as they become saturated in solution.

Table 4.24 shows the final concentrations of the 3 different models. Figure 4.20 shows how the mass distribution of the various ions change as the solution evaporates.

Table 4.25 **Evaporation of leachate solution**

	Original	Model 1	Model 2 Salinity 70000	Model 3	Model 1	Model 2 Salinity 42000	Model 3
Site Name		Using TDS	without ppt	with ppt	Using TDS	without ppt	with ppt
EC (Lab)	54.0	3938					
pH	7.2	7.2	7.0	7.0	7.2	7.0	6.9
pH (Lab)	7.2						
Salinity	960.0	70000			42000		
TDS	1015.0	74009			44405		
Alkalinity (as $CaCO_3$)			94209	255		27324	257
Major ions (mg/L)							
Sodium, Na*	79.5	5797	5757	5732	3478	3490	3480
Potassium, K*	22.6	1648	1636	1630	989	992	989
Calcium, Ca*	113.9	8305	8248	681	4983	5000	542
Magnesium, Mg*	9.9	722	717	314	433	434	254
Chloride, Cl	59	4317	4287	4268	2590	2599	2592
Sulphate, SO_4	46	3354	3331	2388	2013	2019	1965
Carbonate, CO_3	<1		1.38	0.19		20	0.19
Bicarbonate, HCO_3	623	45427	54984	310	27256	33302	314
Nutrients							
Nitrogen (total)	1	73	187	186	44	113	113
Trace elements (µg/L)							
Barium, Ba	1600	116000	116000	20	70000	70000	10
Beryllium, Be	0.10	10	7	7	0	40	40
Cadmium, Cd	1.0	70	70	50	40	40	30
Chromium, Cr	26	1900	1900	0.2	1100	1100	0.2
Copper, Cu	11	800	800	0.8	480	480	0.6
Iron, Fe	6		181000	0		110000	0
Lead, Pb		0	430	430	0	260	260
Nickel, Ni	33	2400	2390	2380	1440	1450	1440
Selenium, Se	28	2000	2030	2020	1230	1230	1230
Strontium, Sr	0	0	3620	3610	0	2190	2190
Thallium, Tl	50	3650	0.7	0.7	2180	0.4	0.4
Uranium, U	0.01	0	0.7	0.7	0	0.4	0.4
Zinc, Zn	0.01	0	32000	27000	0	20000	16000

Note general characteristic values in mg/L unless otherwise stated, pH is dimensionless, - not measured

Again certain elements such as calcium, magnesium, carbonate, sulphate, barium, silica, iron, chromium, copper and zinc are likely to be precipitated as they become saturated in solution.

The most noticeable difference between the models using the groundwater sample and the leachate sample is the high concentrations of cadmium, nickel, selenium and zinc in the modelled final lake waters. High concentrations of these elements are present even when the modelling allows precipitation of saturated minerals.

4.8 HYDROGEOLOGY

When backfilled into the channel, the material is likely to have quite large void spaces due to the inhomogeneous nature of the material. These pore spaces will have the greatest control over the final hydraulic conductivity.

4.8.1 OBSERVATIONS

The physical behaviour of the overburden material was observed during permeability experiments.

Weathered channel horizon

The photographs in Figure 3.2 show some of the boulders are physically unstable when submerged in water. These boulders were composed of clay that has been identified as predominantly smectitic. The clay boulders rapidly broke up, as they became wet, down to a mixture of fine sand to clay size particles that settled as a thick layer. This layer acted as an aquitard restricting the vertical water flow. The horizontal flow may also be effected, as particles that do not immediately settle may block pore spaces as the groundwater moves downstream.

After 24 hours of the sample being emersed in the saturated solution, mineral growth was observed in the larger pore spaces and on the surface of the samples – shown in Figure 4.21.

The reduction in porosity will have an effect on the efficiency in the transport of groundwater.

When sodium chloride was added to the solution cracks formed in the sediment structure, see Figure 4.22, opening new pore spaces. This is likely to increase the permeability. These cracks probably form as smectite clay shrinks under the high sodium chloride conditions.

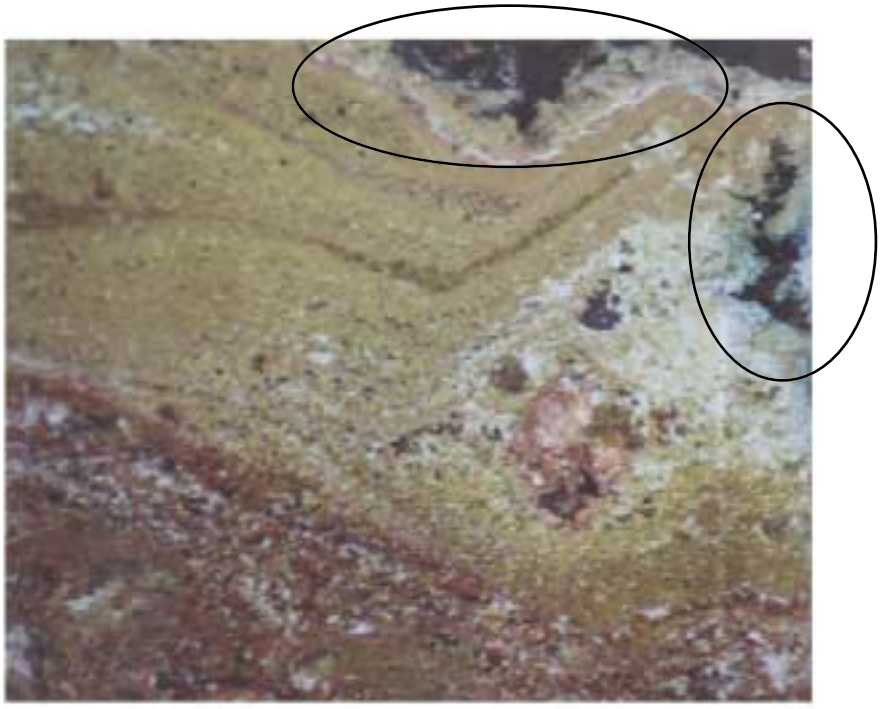
Eastern clay conglomerate

The Eastern clay conglomerate remained fairly stable when submerged in water.

Alluvium

The alluvium was very stable when submerged. However, dolerite in the alluvium will weather to clay minerals after a significant period of time. All the other components of the alluvium were stable and resistant to physical degradation.

AT TIME ZERO



AFTER 24HRS

Figure 4.21

PHOTOGRAPHS SHOWING PRECIPITATION OF MINERALS WHEN EMERSED IN A SATURATED SOLUTION

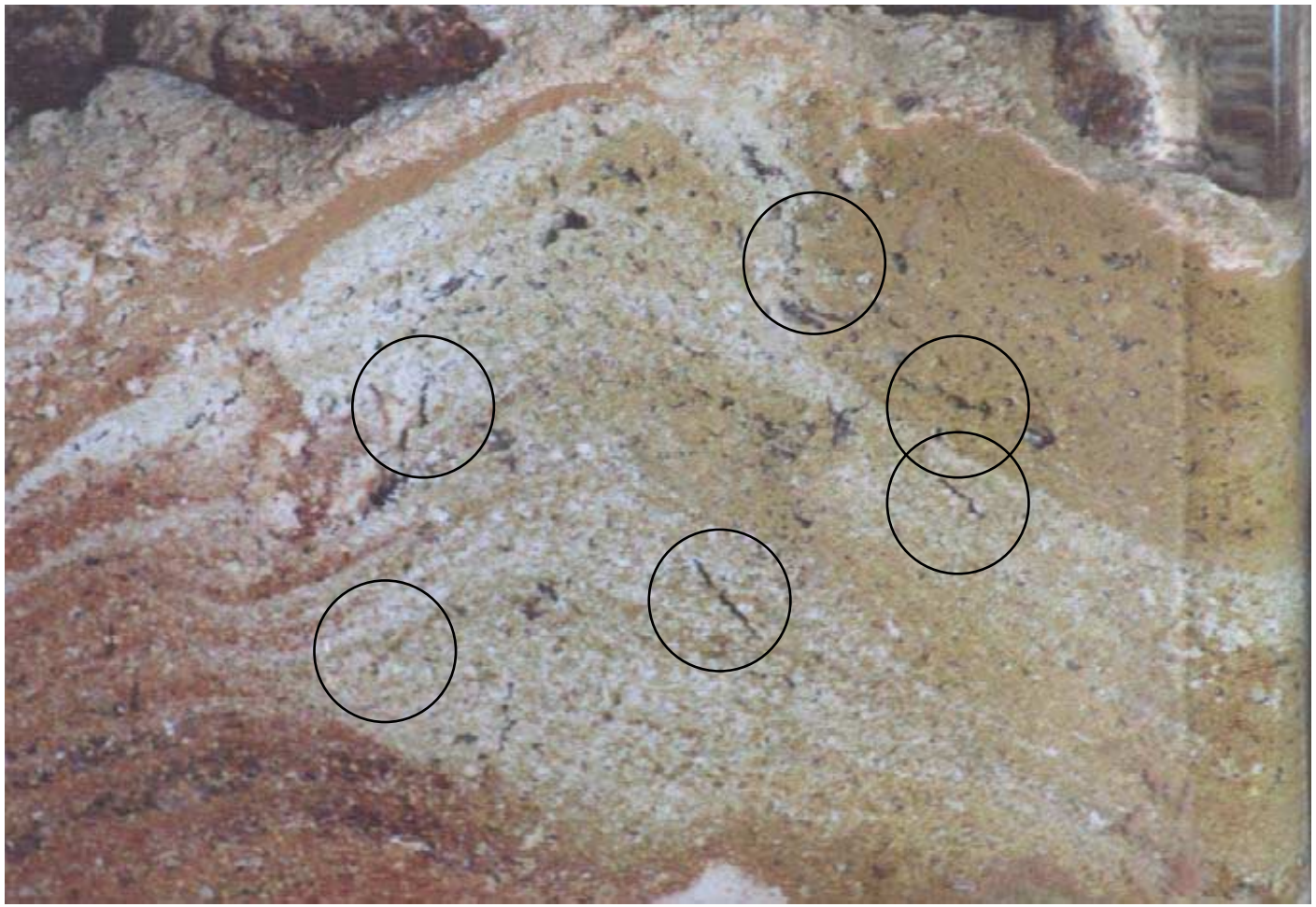


Figure 4.22

PHOTOGRAPH SHOWING CRACKS IN SEDIMENT STRUCTURE THAT FORMED AFTER SODIUM CHLORIDE WAS INTRODUCED

Chapter five

CONCLUSIONS & SUMMARY OF INTEPRETATIONS

Hamersley Iron has a responsibility to make sure the environment is not harmed by their mining operations. This thesis has examined the environmental implications with respect to the groundwater and physical properties of the aquifer once the waste rock is returned to the pit void.

In chapter one the research agenda was outlined along with the literature review and background of the company, mine and area in question. In the second chapter the research methodologies were discussed and in the third chapter the results of the analysis were presented. These results were discussed in chapter 4.

In this final chapter, the conclusions and summary of interpretation of the research are considered and finally, directions for future research are identified.

5.1 SUMMARY OF INTERPRETATIONS

This is a summary of the interpretations discussed in chapter 4.

5.1.1 CHEMISTRY AND HYDROGEOLOGY INTERPRETATION

Chemistry

The regional rocks of the study area have high concentrations of the following elements.

Table 5.1 **Elements that the regional rocks have GAI greater or equal to 1**

	GAI values			
	1	2	3	4
Calcite mineralised shale	Sb, Te	Ba, Ca		
Shale	Mg, Fe	Te		Ba
BIF	Mg, Fe, Sb, Pb, Te		Ba	
Dolerite		Sb, Ba, Te		

Note GAI values are dimensionless

The overburden material was also found to have high concentrations of many elements. These elements are listed below.

Table 5.2 **Elements that the overburden materials have GAI greater or equal to 1**

	GAI values			
	1	2	3	4
Alluvium	As	Fe, Se	Sb, Ba, Te	
Eastern clay conglomerate	Pb, Mo	Fe, As, Se, Te	Sb	Ba
Weathered channel horizon	Mo	Fe, Sb, As, Se	Ba	

Note GAI values are dimensionless

Hydrogeology

The Weathered channel horizon was found to contain bands of smectite clay. This clay is known to swell when wet up to 20 times its dry volume. This may impair the permeability of an aquifer with significant amounts of this clay. A solution with a high sodium chloride concentration may inhibit this swelling.

5.1.2 GROUNDWATER INTERPRETATION

The current groundwater quality is slightly acidic or slightly alkaline, and is typically of calcium/magnesium bicarbonate to sodium carbonate. The majority of the bores sampled met the Australian guidelines for potable water with the exception of the samples listed below.

Table 5.3 **Groundwater sample that exceeded the Australian guidelines for potable water**

Hydrochemical characteristics	Guideline value	YJP99	YJDD106	YJDD262
pH	6.5-8.5	-	5.44	-
Lead, Pb (ug/L)	1	1.73	-	4.08

5.1.3 LEACHATE INTERPRETATION

The leachate tests indicated that the following may occur:

- The pH may rise towards 8.4 due to the buffering of carbonate minerals.
- The TDS may increase as soluble minerals dissolve into the groundwater.
- Conditions for anoinic elements such as antimony, arsenic, cobalt, chromium, gallium and molybdenum will become more favourable due to the rise in pH.
- Minerals such as diaspore, leonhardite, quartz, $ZnSiO_3$ and hematite will start to precipitate as they become saturated in solution.
- Calcium, magnesium, alkalinity, sulphate, iron, silica, barium, copper, chromium and zinc will reduce in concentration as minerals are precipitated.
- Likely to be high concentrations of heavy metals such as cadmium, nickel, selenium and zinc. High concentrations of these elements are present even when the modelling allows precipitation of saturated minerals

5.2 ENVIRONMENTAL IMPACT ON WATER QUALITY

For each closure plan the impact on water quality will be different. Note the diagrams for the closure plans in Figure 1.8.

5.2.1 MINIMUM COST PLAN – MODEL 1

The most cost-effective plan is, when all the ore has been removed, there is no further backfilling of the pit. This would leave the area with two lakes, one by the southwest junction between the CID and the creek and another at the southeast junction.

If this system is not managed, the creek system would start to fill the voids. The groundwater flow downstream of the voids could permanently become reversed and significantly reduce the flow into the Weeli Wolli Creek.

By ensuring the evaporation from the voids does not exceed the inflow to the voids

from the creek system, the Marillana Creek would continue to feed the Weeli Wolli Creek. This could be done by having shallow sloping banks and ensuring pit water levels remain low to reduce the effect of pan evaporation by reducing the surface area of the water. Another method would be divert more water down the Marillana Creek to reduce water loss down stream of the mine site.

Evaporation modelling shows that the TDS of the lakes would slowly increase to a final value of 42,000 mg/L (Peck, 1998). This would not be potable, as the water would exceed many of the Australian guidelines for potable water.

The modelling shows the precipitation of calcium, silicate and iron minerals. This precipitation could block pore space and reduce the permeability of the aquifer.

The saline water within the voids will eventually begin to move downstream along the bottom of the CID as a saline wedge. Due to the difference of densities in the waters, the wedge will not mix well with the surrounding CID and basement groundwaters. With time, the saline plumes from the void could diminish the water quality of the Marillana Creek and the Weeli Wolli Creek that it feeds.

5.2.2 SURFACE WATER MANAGEMENT PLAN – MODEL 2

This option involves a narrow channel being built into the CID to facilitate water flow and to manage the transmissivity of the CID loop. Two lakes would exist as in the first plan. This option would provide easy passage of groundwater through the loop. The effect of evaporation would be less significant and the final TDS in the pit lakes would be 42,000 mg/L, as Peck stated in 1998.

Once again, the lake water would not be potable, as it would exceed many of the Australian guidelines for potable water.

The channel would facilitate mixing of the waters and ensure that there is no reversal of the flow in the creek system. Mixing caused by the channel will slow the increase in TDS in the lake water considerably.

As the TDS of the lake water increases, water quality from the output of the second lake will also be affected.

5.2.3 MAXIMIZATION OF WATER INFLOW PLAN – MODEL 3

By redirecting water from the CID and the creeks into the lakes, the TDS of the lake water could be reduced to 3,900mg/L. The salinity of the pit lakes would not be expected to stabilise for 1000 years. A saline layer would eventually develop. However this option would significantly reduce the level of the groundwater and alluvium waters downstream of the pit as Peck also stated in 1998 and have an adverse affect on the flow of the Weeli Wolli Creek.

5.2.4 ISOLATION PLAN – MODEL 4

This option isolates the waste area from the creek and the CID by forcing the flow along the Marillana Creek rather than allowing it to flow along the CID, as suggested by Peck in 1998.

There would be no outflow, so the water quality downstream of the pit lakes would not be diminished. All groundwater would be directed along the creek system. The water in the lakes would not be potable.

Table 5.4 **Summary and ranking of the closure plans**

	Model 1	Model 2	Model 3	Model 4
Financial Cost	Low	Medium	Medium	High
Environmental factors				
Pit lake water				
TDS	High	High	Medium	High
Heavy metals	High	High	Medium	High
Potable				
Groundwaters (downstream)				
TDS	Low*	Medium-high	Low*	Low
Heavy metals	Low*	Medium-high	Low*	Low
Potable	Yes*	No	Yes*	Yes
Creak waters (downstream)				
TDS	Low*	Medium-high	Low*	Low
Heavy metals	Low*	Medium-high	Low*	Low
Potable	Yes*	No	Yes*	Yes
Hydrogeological factors				
Local Aquifers	Reversed	Reduced	Reversed	Same
Local Creek flow	Reversed	Reduced	Reversed	Same
Down Stream flow	Reduced	Reduced	Reduced	Same
Rank	4	2	3	1

** As flow will be reversed and coming from other sources*

5.3 LIMITATIONS

This studies results and interpretations have limitations, as do all projects. These limitations are detailed below.

5.3.1 LITERATURE REVIEW

The majority of the literature review was undertaken at the beginning of this study, some years ago now, because of this recent work on similar to this study has not been included. The topics of the review could have been broader, however the lines had to be drawn somewhere due to time constraints.

Some of the data used in this report is based on information gathered in literature reviews, particularly the work of Peck (1998). These reports and papers have limitations too, for example some of the historical hydrogeological data for parts of the study area is incomplete and only stretches back 30 years.

5.3.2 CHEMISTRY

Where possible new samples were taken and analysed by the schools of School of Applied Geology, Curtin University. Bore hole rock samples, historical water samples and field data were collected and analysed by other organisation. The other organisations analyses focused on a smaller group of hydrochemical characteristics than the school of Applied Geology. Quality control data was only available for the samples analysed at Curtin University. Detection limits varied due to the different

analytical methods used and improvements in detection limits over the last ten years. The chemical results are compiled from a number of sources.

The seasonal hydrochemical data is limited so it is difficult to drawn any conclusions from this.

The higher pH recorded for water samples in the laboratory compared with the field values would by due to the loss of CO_2 that is less soluble under normal atmospherical conditions. Because of this the field pH values were used in calculations and the laboratory values was used only if no field value was available.

Contamination of sample were possible was identified and either the results were disregarded or discussed in the interpretation.

Where samples failed the QA/QC procedures or values appeared erroneous the analysis was repeated.

5.3.3 LEACHATE TESTS

The fine grained leachate tests had significantly increased extraction rates. It should be noted that in the real world these rates would be much slower as groundwater would flow around the rocks in monolithic form, reducing the surface contact area significantly.

5.3.4 GEOCHEMICAL MODELLING OF GROUNDWATERS AND PIT WATERS

PHREEQC (Parkhurst, 1995) is a geochemical program that is applicable for most hydrochemical situations. The program is adequate for aqueous solutions of low ionic strength. In solutions of high ionic strength the expressions of ion-association and Debye Hückel expressions breakdown. Although extensions to the code have been made to fit sodium chloride solutions of high ionic strength. Thus the evaporation pit waters models may not be accurate (Parkhurst and Appelo, 1999).

The databases that the program uses should be regarded are preliminary as they have been compiled from a number of literature sources (Parkhurst and Appelo, 1999).

The program has shown inconsistencies in handling small numbers during inverse modelling (Parkhurst and Appelo, 1999).

5.4 FUTURE RESEARCH

The water quality downstream of the pit lakes will change and the environmental impact of the groundwater will depend on which closure plan is chosen.

Further leachate testing could be undertaken to identify elements of environmental interest, the final pH and other environmental values of the pit lakes.

All plans leave behind pit lakes containing leachate water from the backfilled waste. Further modelling of the pit lake water and groundwater geochemical plumes that may develop from the lakes could also be researched further.

Identification of how pit lake water and groundwaters from the pit lakes may affect fauna and flora in the downstream creek systems is another aspect of possible future research.

The hydrogeology studies of this thesis show that swelling clays may reduce the hydraulic conductivity. However, the experiments conducted in this thesis were on a small scale. The hydrogeology of the waste rock could be studied on a larger scale to improve the representativeness of the results is also a valid topic for further research.

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APPENDICES

Table A.1 **Australian guidelines for potable water.**

Hydrochemical characteristics	guideline values
General characteristics	
pH	6.5-8.5
TDS	500
Major ions (mg/L)	
Iron, Fe	0.3
Manganese, Mn	0.5
Fluoride, F	1.5
Chloride, Cl	250
Sulphate, SO4	500
Hardness (as $CaCO_3$)	200
Nutrients	
Nitrate (as Nitrate)	50
Trace elements (µg/L)	
Aluminium,Al	200
Antimony, Sb	3
Arsenic, As	7
Barium, Ba	700
Cadmium, Cd	2
Copper, Cu	1000
Chromium, Cr	50
Lead, Pb	1
Mercury, Hg	1
Molybdenum, Mo	100
Nickel. Ni	2
Selenium, Se	10
Zinc, Zn	3000

Note general characteristic values im mg/L unless stated, pH is dimensionless
National Health and Medical Research Council and Agriculture and Resource Management Council of Australia and New Zealand 1996

Table A.2 **The USEPA water quality standards**

Hydrochemical characteristics	USEPA Water Quality Standards		
Contaminant	MCL	MCLG	Secondary Standards
General characteristics			
pH	-	-	6.5-8.5
TDS	-	-	500
Major ions			
Iron, Fe	-	-	0.3
Manganese, Mn	-	-	0.05
Fluoride, F	-	-	4
Chloride, Cl	-	-	250
Sulphate, SO4	-	-	250
Hardness (as $CaCO_3$)	-	-	50
Nutrients			
Nitrogen (total)	-	-	-
Nitrate (as N)	-	-	10
Trace elements			
Arsenic, As	0.05	0.05	-
Barium, Ba	-	-	1.0
Bismuth, Bi	-	-	-
Cadmium, Cd	0.01	0.005	-
Copper, Cu	-	-	1.0
Lead, Pb	0.05	0.02	-
Mercury, Hg	-	-	0.002
Selenium, Se	-	-	0.01
Zinc, Zn	-	-	5.0

Note: Maximum Contaminant Level (MCL). Maximum Contaminant Level Goals (MCLG) Secondary Drinking Water Standards
pH has no units

Table A.3 **Historical data -hydrochemical characteristics of the CID groundwaters**

Hydrochemical characteristic	PU06	GS53	GS8	YC218	YC216	YC217
Year of sampling	1992	1992	1992	1992	1992	1992
General characteristics						
pH	-	7.2	7.2	-	-	-
EC (lab) (uS/cm)	-	-	-	-	-	-
TDS (at180 °C)	460	525	460	330*	420*	480*
Major ions						
Sodium, Na	79	71	61	-	-	-
Potassium, K	-	9	6	-	-	-
Magnesium, Mg	46	46	36	-	-	-
Calcium, Ca	44	34	35	-	-	-
Iron(II), Fe	-	<0.1	-	-	-	-
Iron(III), Fe	<0.05	-	-	-	-	-
Manganese, Mn	0.13	-	-	-	-	-
Fluoride, F	0.5	0.8	-	-	-	-
Chloride, Cl	96	88	80	-	-	-
Sulphate, SO_4	41	32	30	-	-	-
Bicarbonate, HCO_3	300	350	290	-	-	-
Carbonate, CO_3	-	-	<5	-	-	-
Neutral species						
Total silicon (as SiO_2)	<0.03	60	-	-	-	-
Nutrients						
Nitrate (as N)	2.3	4.0	-	-	-	-
Trace elements						
Aluminium, Al	<0.01	-	-	-	-	-
Arsenic, As	<0.03	-	-	-	-	-
Cadmium, Cd	0.02	-	-	-	-	-
Chromium, Cr	<10	-	-	-	-	-
Copper, Cu	<0.01	-	-	-	-	-
Lead, Pb	<0.02	-	-	-	-	-
Zinc, Zn	<0.02	-	-	-	-	-

Note all values mg/L unless otherwise stated, pH is dimensionless, * TDS estimated using electrical conductivity, - not measured. Peck (1995)

Table A.3(cont.) **Historical data -hydrochemical characteristics of the CID groundwaters**

Hydrochemical characteristic	YC215	DW1	YC214	YC213	YC207	DW2
Year of sampling	1992	1992	1992	1992	1992	1992
General characteristics						
pH	-	6.7	-	-	-	6.2
EC (lab) (uS/cm)	-	720	-	-	-	835
TDS (at180 °C)	380*	-	420*	450*	510*	535
Major ions						
Sodium, Na	-	60	-	-	-	75
Potassium, K	-	5	-	-	-	6
Magnesium, Mg	-	45	-	-	-	50
Calcium, Ca	-	40	-	-	-	45
Iron(II), Fe	-	0.9	-	-	-	0.65
Iron(III), Fe	-	-	-	-	-	-
Manganese, Mn	-	-	-	-	-	-
Fluoride, F	-	<0.1	-	-	-	<0.1
Chloride, Cl	-	110	-	-	-	125
Sulphate, SO_4	-	50	-	-	-	55
Bicarbonate, HCO_3	-	280	-	-	-	315
Carbonate, CO_3	-	0	-	-	-	-
Neutral species						
Total silicon (as SiO_2)	-	64	-	-	-	42
Nutrients						
Nitrate (as N)	-	3.0	-	-	-	4.0
Trace elements						
Aluminium, Al	-	-	-	-	-	-
Arsenic, As	-	-	-	-	-	-
Cadmium, Cd	-	-	-	-	-	-
Chromium, Cr	-	-	-	-	-	-
Copper, Cu	-	-	-	-	-	-
Lead, Pb	-	-	-	-	-	-
Zinc, Zn	-	-	-	-	-	-

Note all values mg/L unless otherwise stated, pH is dimensionless, * TDS estimated using electrical conductivity, - not measured. Peck (1995)

Table A.3(cont.) **Historical data -hydrochemical characteristics of the CID groundwaters**

Hydrochemical characteristic	YC205	YC147	YM104	YM114	YM118
Year of sampling	1992	1992	1992	1992	1992
General characteristics					
pH	-	-	-	-	-
EC (lab) (uS/cm)	-	-	-	-	-
TDS (at180 °C)	470*	147*	590	400	400
Major ions					
Sodium, Na	-	-	91	65	62
Potassium, K	-	-	-	-	-
Magnesium, Mg	-	-	56	39	38
Calcium, Ca	-	-	59	37	42
Iron(II), Fe	-	-	-	-	-
Iron(III), Fe	-	-	0.05	0.05	<0.03
Manganese, Mn	-	-	<0.01	<0.01	<0.01
Fluoride, F	-	-	0.5	0.5	0.4
Chloride, Cl	-	-	120	72	70
Sulphate, SO_4	-	-	57	41	38
Bicarbonate, HCO_3	-	-	380	270	280
Carbonate, CO_3	-	-	-	-	-
Neutral species					
Total silicon (as SiO_2)	-	-	-	-	-
Nutrients					
Nitrate (as N)	-	-	75	1.3	4.6
Trace elements					
Aluminium, Al	-	-	<0.05	0.05	<0.05
Arsenic, As	-	-	<0.03	<0.03	<0.03
Cadmium, Cd	-	-	<0.01	<0.01	<0.01
Chromium, Cr	-	-	<0.01	<0.01	<0.01
Copper, Cu	-	-	<0.02	<0.02	<0.02
Lead, Pb	-	-	<0.02	<0.02	<0.02
Zinc, Zn	-	-	0.02	0.052	0.013

Note all values mg/L unless otherwise stated, pH is dimensionless, * TDS estimated using electrical conductivity, - not measured. Peck (1995)

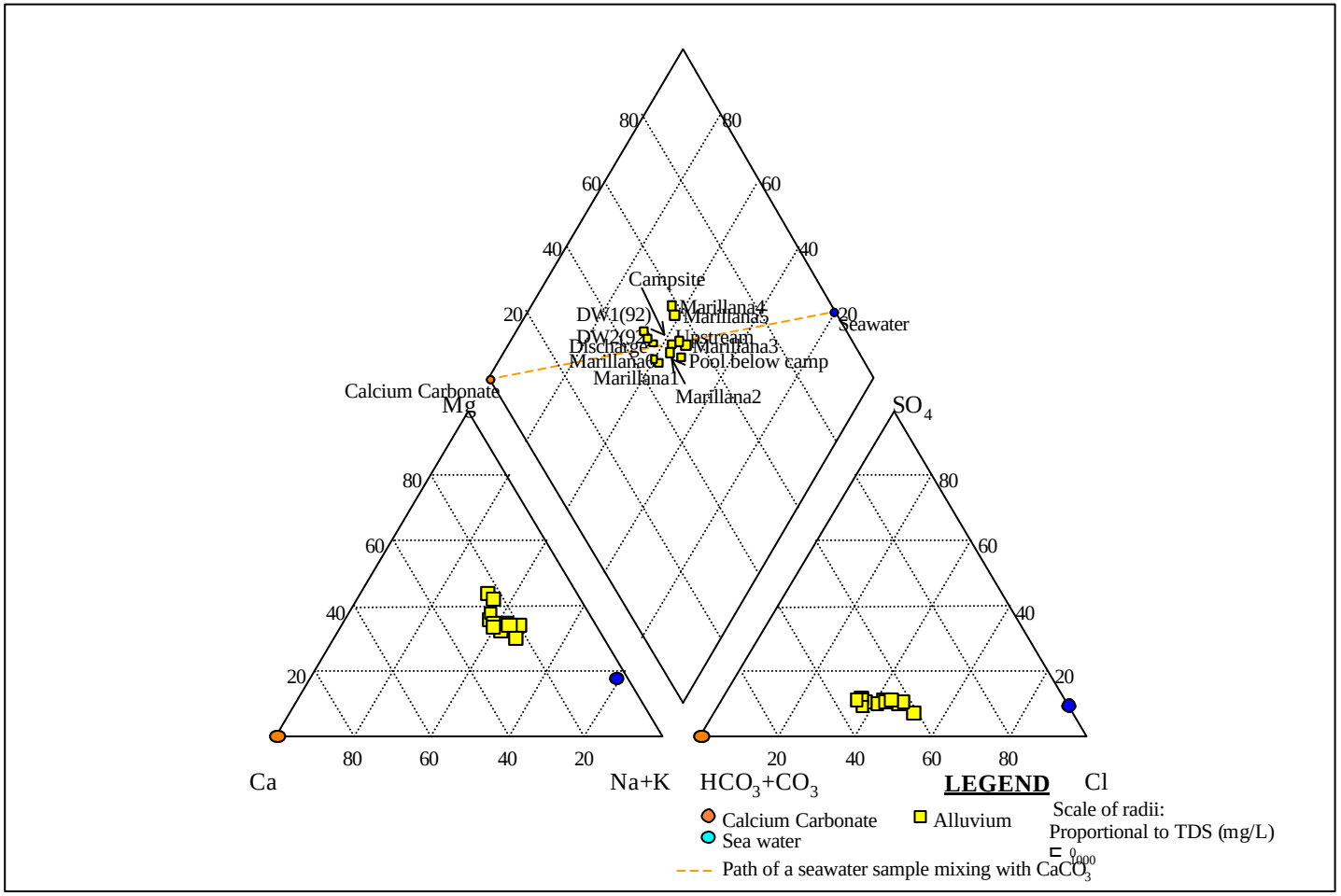

Figure A.1

MAJOR ION COMPOSITION OF THE HISTORICAL ALLUVIUM GROUNDWATER AND SURFACE WATERS

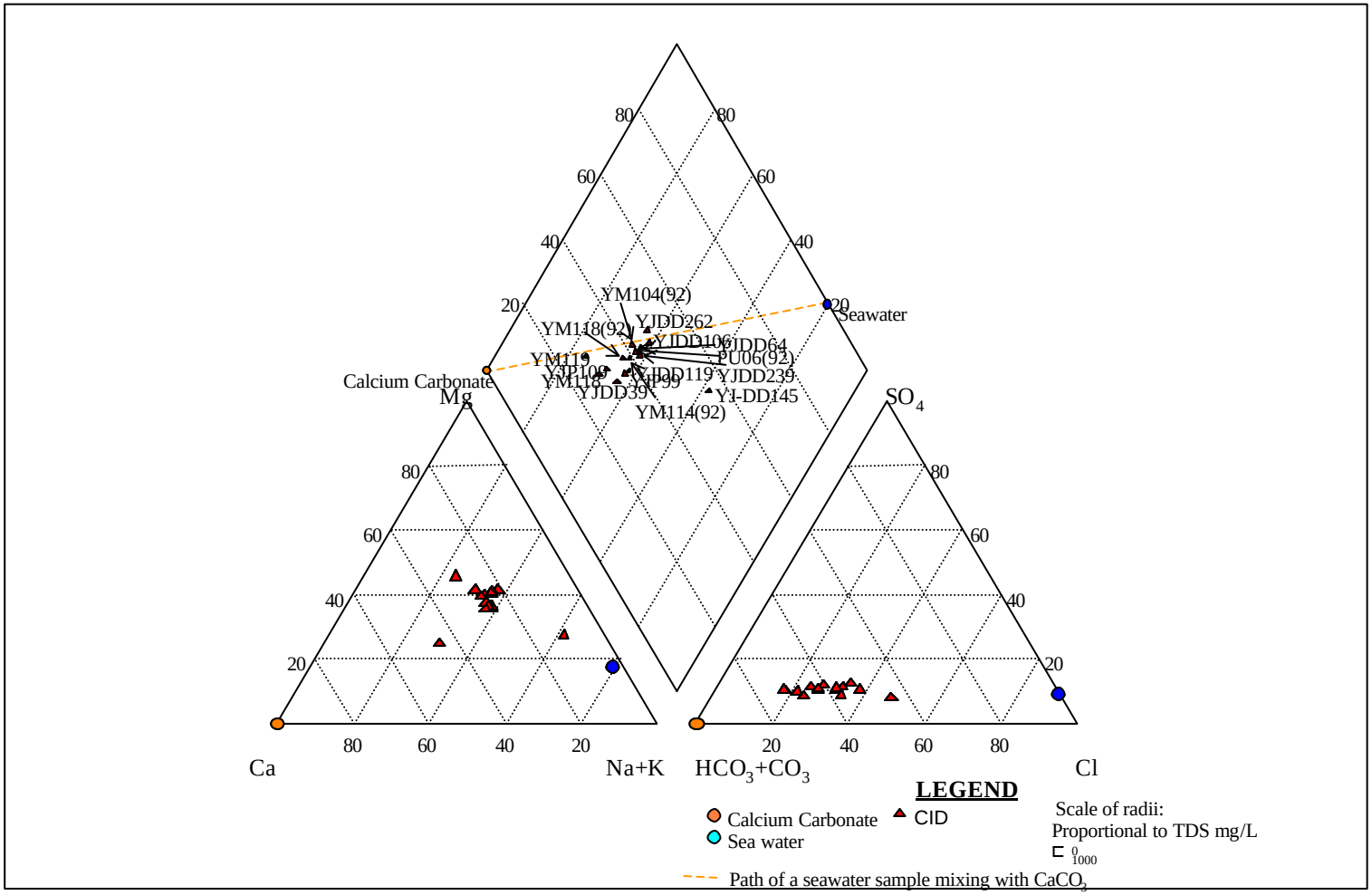

Figure A.2

MAJOR ION COMPOSITION OF THE HISTORICAL CID GROUNDWATER

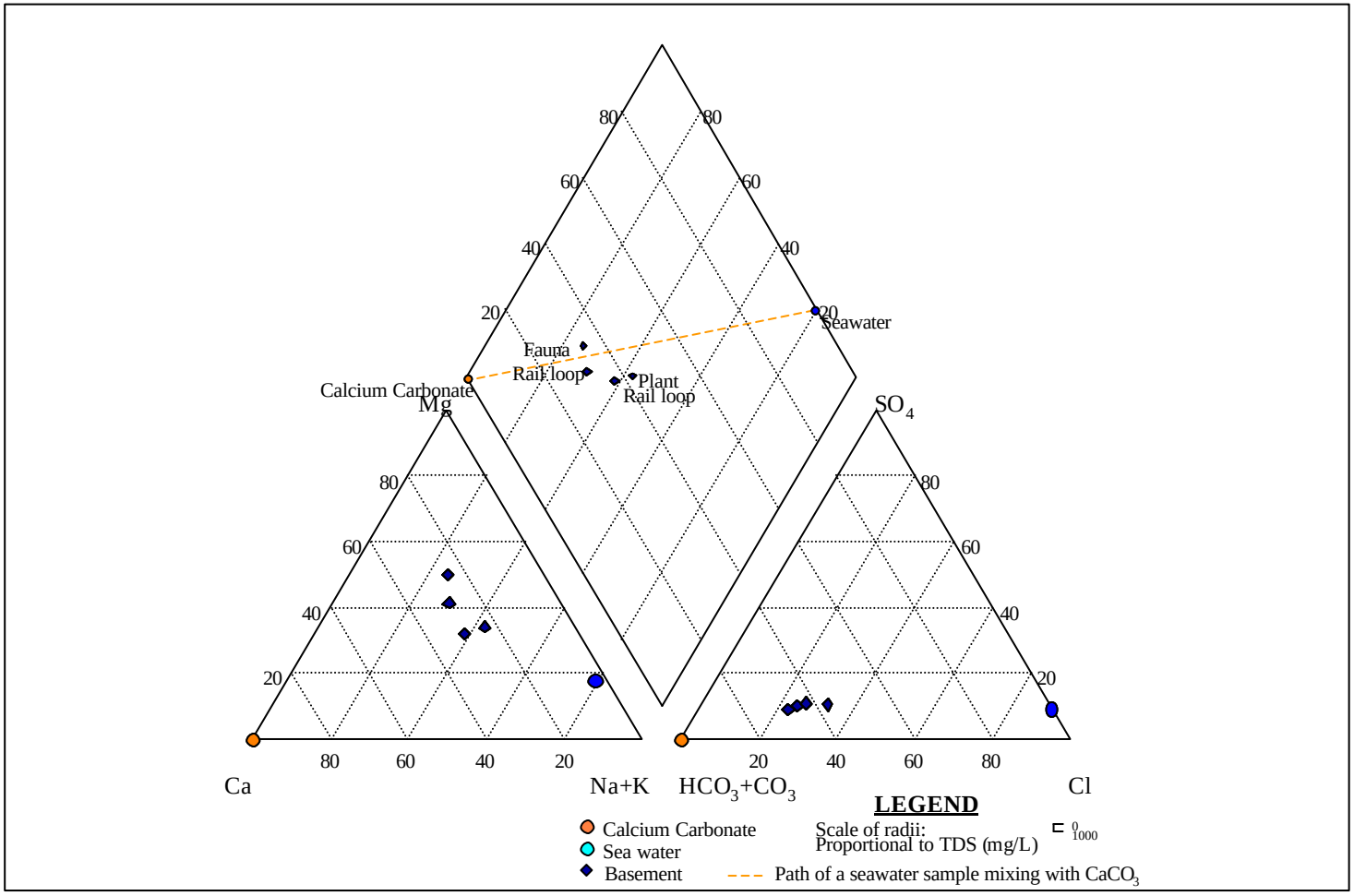

Figure A.3

MAJOR ION COMPOSITION OF THE HISTORICAL BASEMENT GROUNDWATER

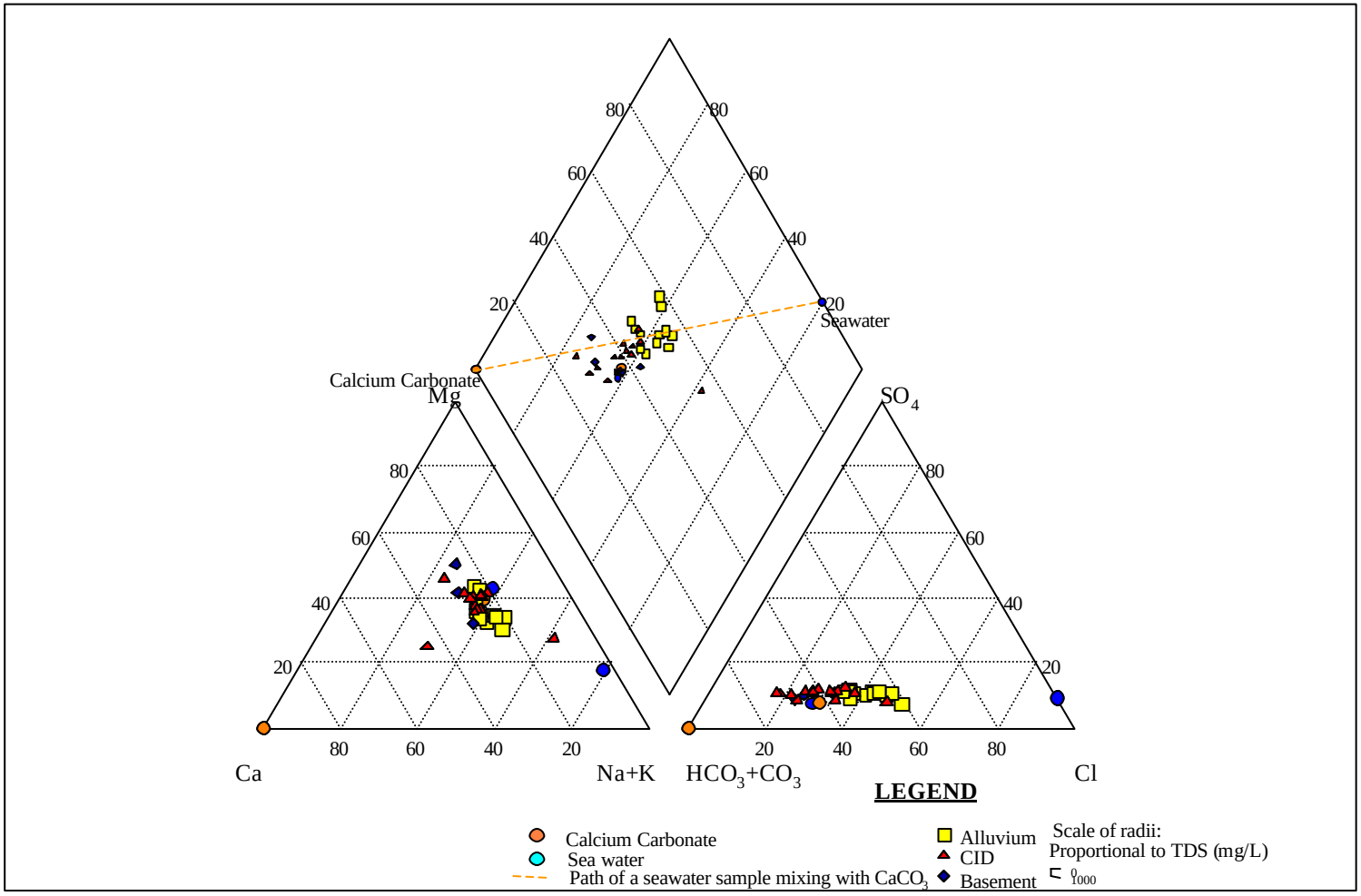

Figure A.4

MAJOR ION COMPOSITION OF THE HISTORICAL GROUNDWATER

Table A.4 **Summary of the associated elements (all rock samples)**

$r_{x,y}$	Element	Associated elements
1.00	zirconium	palladium
0.99 - 0.9	antimony	bismuth, lead and tellurium
	bismuth	Antimony and lead
	cadmium	hafnium, palladium and zirconium
	hafnium	gallium, niobium, thorium and tin
	indium	palladium, thorium and tin
	iron	Germanium
	lanthanum	praseodymium
	lead	bismuth, antimony and tellurium
	mercury	tungsten (contamination during preparation)
	palladium	cadmium, hafnium and indium
	rubidium	thallium
	tantalum	niobium
	tellurium	antimony and lead
	thallium	rubidium
	thorium	hafnium, indium and tin,
	tin	hafnium, indium and thorium
	yttrium	dysprosium, Erbium, holmium and terbium
	zinc	phosphorus
	zirconium	cadmium and hafnium
0.89 - 0.8	aluminium	Hafnium, palladium, tantalum and titanium
	antimony	indium and thorium
	bismuth	tellurium
	cadmium	gallium, niobium, thorium and tin
	chromium	tellurium
	copper	lead and tellurium
	gallium	cadmium, indium, palladium, thorium, tin, uranium, vanadium, zirconium and hafnium
	hafnium	Gallium, indium, niobium, tantalum and uranium
	indium	lead, gallium, palladium, uranium vanadium and zirconium
	lanthanum	gadolinium and neodymium
	lead	copper, indium and thorium,
	niobium	cadmium, hafnium, palladium, titanium and zirconium
	palladium	aluminium, gallium, indium, niobium, thorium and tin
	rubidium	silica
	silica	rubidium
	tantalum	Aluminium, tin, titanium and zirconium
	tellurium	bismuth, chromium and copper,
	thorium	antimony, cadmium, gallium, lead, palladium, titanium, vanadium and zirconium
	tin	cadmium, gallium, palladium, tantalum, uranium and zirconium
	titanium	aluminium, niobium and tantalum
	uranium	gallium, hafnium, indium and tin,
	vanadium	gallium, indium and thorium
	yttrium	europium, gadolinium, lutetium and samarium
	zirconium	gallium, indium, niobium, tantalum, thorium and tin,
< -0.7	aluminium	Iron and germanium
	germanium	aluminium, rubidium and silica
	iron	Silica and rubidium
	silica	Iron and germanium

Table A.4(cont.) **Summary of the associated elements (ALL rock samples)**

$r_{x,y}$	Element	Associated elements
1.00	tin	hafnium
	zirconium	palladium and tin
0.99 - 0.9	antimony	iron, arsenic, cadmium, copper, germanium, indium, lead palladium, tellurium and thorium
	arsenic	iron, cadmium, copper, germanium, indium, lead, tellurium, thorium
	bismuth	cadmium, gallium, hafnium, indium, molybdenum, niobium, palladium, thorium, tin, uranium, vanadium and zirconium
	cadmium	iron, antimony, arsenic, bismuth, copper, gallium, germanium, hafnium, indium, lead, molybdenum, palladium, tellurium, thorium, tin, vanadium, yttrium and zirconium
	chromium	lanthanum
	cobalt	tantalum
	copper	antimony, arsenic, cadmium, germanium, lead, tellurium, thorium,
	gallium	bismuth, cadmium, hafnium, indium, molybdenum, niobium, palladium, thorium, tin, uranium, vanadium and zirconium
	germanium	iron, antimony, arsenic, cadmium, copper, lead, palladium, tellurium, thorium and yttrium
	hafnium	bismuth, cadmium, gallium, indium, molybdenum, niobium, palladium, thorium, tin and yttrium
	indium	antimony, arsenic, bismuth, cadmium, gallium, lead, molybdenum, palladium, tellurium, thorium, tin, uranium and zirconium
	iron	antimony, arsenic, cadmium, copper, germanium, lead and tellurium
	lanthanum	praseodymium
	lead	iron, antimony, arsenic, cadmium, copper, germanium, indium, tellurium and thorium
	mercury	tungsten (contamination during preparation)
	molybdenum	bismuth, cadmium, gallium, hafnium, indium, niobium, palladium, thorium, tin, uranium, vanadium and zirconium
	nickel	titanium,
	niobium	bismuth, gallium, hafnium, molybdenum, palladium, thorium, tin, uranium, vanadium and zirconium
	palladium	antimony, bismuth, cadmium, gallium, germanium, hafnium, indium, molybdenum, niobium, tellurium, thorium, tin, uranium, vanadium and zirconium
	phosphorus	zinc
	rubidium	silica and thallium
	tantalum	cobalt
	tellurium	iron, antimony, arsenic, cadmium, copper, germanium, indium, lead, palladium, thorium and zirconium,
	thallium	silica and rubidium.
	thorium	antimony, arsenic, bismuth, cadmium, copper, gallium, germanium, hafnium, indium, lead, molybdenum, palladium, tellurium, tin, uranium, vanadium and zirconium
	tin	bismuth, cadmium, gallium, indium, molybdenum, niobium, palladium, uranium and vanadium
	titanium	nickel
	uranium	bismuth, gallium, hafnium, indium, molybdenum, palladium, thorium, tin and zirconium
	vanadium	bismuth, cadmium, gallium, hafnium, molybdenum, niobium, palladium, thorium, tin, yttrium and zirconium,
	yttrium	cadmium, germanium, vanadium, dysprosium, Erbium, holmium, lutetium, terbium, thulium and ytterbium
	zinc	phosphorus
	zirconium	bismuth, cadmium, gallium, hafnium, indium, molybdenum, niobium, palladium, tellurium, thorium, tin, uranium and vanadium
0.89 - 0.8	aluminium	palladium, tantalum and titanium
	antimony	bismuth, gallium, hafnium, molybdenum, tin,, vanadium, yttrium and zirconium
	arsenic	bismuth, hafnium, molybdenum, tin, uranium, vanadium and zirconium

	barium	tungsten and cerium
	bismuth	Antimony, arsenic, copper, germanium, lead and tellurium
	cadmium	uranium and ytterbium
	chromium	strontium and gadolinium
	cobalt	hafnium, indium, palladium, tin, vanadium, yttrium and zirconium
	copper	lead and tellurium
	gallium	antimony, germanium, tellurium and yttrium,
	germanium	bismuth, gallium, hafnium, indium, molybdenum, tin, vanadium, zirconium, erbium, lutetium and ytterbium
	hafnium	antimony, arsenic, copper, germanium, lead and tellurium
	indium	iron, copper, germanium, niobium and vanadium
	iron	indium, thorium and yttrium
	lanthanum	gadolinium and neodymium
	lead	bismuth, hafnium, palladium, tin and zirconium
	molybdenum	antimony, arsenic, germanium, tellurium, yttrium and ytterbium
	niobium	cobalt, indium, tantalum, thorium and uranium,
	palladium	arsenic, copper, lead, yttrium and ytterbium
	rubidium	magnesium
	strontium	chromium
	tantalum	niobium
	tellurium	bismuth, gallium, hafnium, molybdenum, tin, vanadium and yttrium
	thorium	iron, niobium and yttrium
	tin	antimony, arsenic, copper, germanium, lead and tellurium,
	tungsten	barium,
	uranium	arsenic, cadmium, niobium and vanadium
	vanadium	antimony, arsenic, copper, germanium, indium, tellurium, uranium, dysprosium, erbium, europium, holmium, lutetium, thulium and ytterbium
	yttrium	antimony, copper, gallium, molybdenum, palladium, tellurium, thorium, zirconium, europium, gadolinium, neodymium, praseodymium and samarium
	zirconium	antimony, arsenic, copper, germanium, lead and yttrium
< -0.7	aluminium	cerium, phosphorus and zinc
	antimony	magnesium, silica, rubidium and thallium,
	arsenic	silica, rubidium and thallium,
	barium	arsenic, bismuth, cadmium, gallium, hafnium, indium, molybdenum, niobium, palladium, thorium, tin, uranium, vanadium and zirconium
	beryllium	cobalt, gallium, hafnium, molybdenum, niobium, tantalum, tin and uranium
	bismuth	silica and rubidium,
	cadmium	magnesium, silica, barium, rubidium and thallium
	chromium	sulphur
	cobalt	Beryllium and mercury
	gallium	silica, barium, beryllium, mercury and tungsten
	germanium	Silica, rubidium and thallium
	germanium	aluminium, rubidium and silica
	hafnium	silica, barium, beryllium, mercury, rubidium and tungsten
	indium	magnesium, silica, barium, rubidium and thallium
	iron	magnesium, silica, rubidium and thallium
	lanthanum	sulphur
	lead	magnesium, silica, rubidium and thallium
	magnesium	iron, antimony, arsenic, bismuth, cadmium, copper, indium, lead and thorium
	manganese	titanium, nickel, dysprosium, europium, gadolinium, neodymium, praseodymium, samarium, terbium and thulium.
	mercury	cobalt, gallium, hafnium, molybdenum, niobium, palladium, tantalum, uranium, vanadium, yttrium, zirconium, dysprosium, erbium, europium, holmium, lutetium, samarium, terbium, thulium and ytterbium
	molybdenum	silica, barium, beryllium, mercury, rubidium and tungsten
	nickel	manganese

niobium	barium, beryllium, mercury and tungsten,
palladium	silica, barium, mercury, rubidium and tungsten,
phosphorus	aluminium
rubidium	iron, antimony, arsenic, bismuth, cadmium, copper, germanium, hafnium, indium, lead, molybdenum, palladium tellurium, and thorium tin uranium, vanadium, yttrium and zirconium
silica	iron, antimony, arsenic, bismuth, cadmium, copper, gallium, germanium, hafnium, indium, lead, molybdenum, palladium tellurium, and thorium tin uranium, vanadium, yttrium, zirconium, dysprosium, erbium, holmium, lutetium, terbium, thulium and ytterbium
strontium	sulphur
sulphur	chromium, germanium, lanthanum strontium, yttrium, gadolinium, lutetium, neodymium, praseodymium, samarium, terbium and ytterbium
tantalum	beryllium and mercury
tellurium	magnesium, silica, rubidium and thallium
thallium	iron, antimony, arsenic, cadmium, copper, germanium, indium, lead and tellurium
thorium	magnesium, silica, barium and rubidium
tin	silica, barium, beryllium and rubidium
titanium	magnesium
tungsten	gallium, hafnium, molybdenum, niobium, palladium, uranium, vanadium, yttrium, zirconium, dysprosium, erbium, europium, holmium, lutetium, terbium, thulium and ytterbium
uranium	silica, barium, beryllium, mercury, rubidium and cerium
vanadium	silica, barium, mercury, rubidium and tungsten
yttrium	sulphur, silica, mercury, rubidium and tungsten
zinc	aluminium
zirconium	silica, barium, mercury, rubidium and tungsten

Table A.4(cont.) **Summary of the associated elements (ECC rock samples)**

$r_{x,y}$	Element	Associated elements
1.00	zirconium	palladium
0.99 - 0.9	cadmium	hafnium, palladium and zirconium
	hafnium	cadmium, niobium, palladium, thorium, tin and zirconium
	indium	thorium and tin
	lanthanum	praseodymium
	magnesium	tungsten
	niobium	hafnium, palladium, tantalum and zirconium
	palladium	cadmium, hafnium, thorium, tin, uranium, vanadium and zirconium
	tantalum	niobium
	thorium	hafnium, indium, palladium, tin and zirconium
	tin	hafnium, indium, palladium, thorium and tin
	tungsten	magnesium
	yttrium	dysprosium, Erbium, holmium, lutetium, terbium and thulium
	zirconium	cadmium, hafnium, niobium, palladium and thorium
0.89 - 0.8	aluminium	tantalum
	barium	sulphur
	bismuth	mercury
	cadmium	indium, niobium, thorium, tin
	calcium	lanthanum
	chromium	rubidium and thallium
	gallium	vanadium
	germanium	iron and vanadium
	hafnium	indium and tantalum
	indium	cadmium, palladium and zirconium
	iron	germanium
	lanthanum	calcium, cerium, europium, gadolinium, neodymium and samarium
	magnesium	silica
	mercury	bismuth
	molybdenum	erbium, lutetium, thulium and ytterbium
	niobium	titanium, cadmium and tin
	palladium	chromium
	phosphorus	zinc
	rubidium	magnesium
	silica	magnesium, strontium and tungsten
	strontium	silica
	sulphur	barium
	tantalum	aluminium, titanium, hafnium, palladium, tin, zirconium
	thallium	chromium, rubidium,
	thorium	cadmium
	tin	cadmium, niobium, tantalum and zirconium
	titanium	Niobium and tantalum
	tungsten	silica
	vanadium	gallium and zirconium
	yttrium	europium, neodymium, praseodymium, samarium and ytterbium
	zinc	phosphorus
	zirconium	indium, tantalum, tin and vanadium
< -0.7	aluminium	cerium, phosphorus and zinc
	germanium	silica, rubidium and thallium
	iron	silica, strontium and tungsten
	magnesium	iron, antimony, arsenic, bismuth, cadmium, copper, indium, lead and thorium
	molybdenum	silica, barium, beryllium, mercury, rubidium and tungsten
	silica	Iron and germanium
	strontium	Iron and germanium
	tungsten	Iron and germanium

Table A.4(cont.) **Summary of the associated elements (WCH rock samples)**

$r_{x,y}$	Element	Associated elements
1.00	hafnium	palladium and zirconium
	palladium	hafnium and zirconium
	zirconium	hafnium and palladium
0.99 - 0.9	aluminium	titanium, cadmium, gallium, hafnium, indium, lead, palladium, tantalum, thorium, tin and zirconium
	antimony	chromium,
	bismuth	gallium, hafnium, indium, palladium, thorium, tin and zirconium
	cadmium	aluminium, titanium, hafnium, indium, palladium, rubidium, tantalum, thorium, tin and zirconium
	calcium	magnesium
	chromium	antimony and vanadium
	gallium	aluminium, titanium, bismuth, indium, palladium, thorium, tin and zirconium
	hafnium	aluminium, titanium, bismuth, cadmium, indium, rubidium, tantalum, thorium, tin and uranium
	indium	aluminium, titanium, bismuth, cadmium, hafnium, lead, palladium, thorium, tin and zirconium
	lanthanum	yttrium, europium, gadolinium, neodymium, praseodymium, samarium and terbium
	lead	aluminium and indium
	magnesium	calcium
	mercury	tungsten
	niobium	tantalum
	palladium	aluminium, titanium, bismuth, cadmium, gallium, indium, rubidium, tantalum, thorium, tin and uranium,
	rubidium	cadmium, hafnium, palladium and thorium,
	tantalum	aluminium, titanium, cadmium, hafnium, niobium, palladium, thorium, tin and zirconium
	thorium	aluminium, titanium, bismuth, cadmium, gallium, hafnium, indium, palladium, rubidium, tantalum, tin, uranium and zirconium
	tin	aluminium, titanium, bismuth, cadmium, gallium, hafnium, indium, palladium, tantalum, thorium, uranium and zirconium
	titanium	aluminium, cadmium, gallium, hafnium, indium, palladium, tantalum, thorium, tin and zirconium
	tungsten	mercury
	uranium	hafnium, palladium, thorium, tin and zirconium
	vanadium	chromium,
	yttrium	lanthanum, dysprosium, Erbium, gadolinium, holmium and terbium
	zirconium	aluminium, titanium, bismuth, cadmium, gallium, indium, tantalum, tin, uranium
0.89 - 0.8	aluminium	bismuth, nickel and uranium
	antimony	bismuth, gallium, indium, lead, tin,
	barium	thulium
	bismuth	aluminium, titanium, antimony, cadmium, tantalum and uranium
	cadmium	bismuth, gallium and uranium
	calcium	strontium
	chromium	gallium and tellurium
	copper	nickel
	gallium	antimony, cadmium, chromium, hafnium, lead, nickel, tantalum and uranium
	germanium	iron
	hafnium	antimony
	indium	antimony, rubidium, tantalum and uranium
	iron	germanium
	lanthanum	dysprosium and holmium
	lead	titanium, antimony, cadmium, gallium, nickel, palladium, tantalum, thorium, tin and uranium
	nickel	aluminium, titanium, copper, gallium, lead and cerium
	niobium	titanium

	palladium	silica, lead,
	rubidium	aluminium, silica, titanium, indium, tin, uranium and zirconium
	silica	hafnium, palladium, rubidium, tin, zirconium
	strontium	calcium
	tantalum	bismuth, gallium, lead, uranium
	tellurium	chromium
	thallium	barium
	thorium	lead
	tin	silica, antimony, lead and rubidium
	titanium	bismuth, lead, nickel, niobium, rubidium, uranium
	uranium	aluminium, titanium, bismuth, cadmium, gallium, indium, lead, rubidium and tantalum
	yttrium	europium, neodymium, praseodymium and samarium
	zinc	sulphur
	zirconium	silica and rubidium
< -0.7	aluminium	iron, arsenic and germanium
	arsenic	cadmium, hafnium, nickel, niobium, palladium, tantalum, tin, uranium, zirconium, cerium, erbium, holmium, lutetium, thulium and ytterbium
	cadmium	iron and germanium
	copper	phosphorus
	gallium	iron,
	germanium	aluminium, silica, titanium, cadmium, hafnium, indium, palladium, rubidium, tantalum, thorium, tin, uranium and zirconium
	hafnium	iron, arsenic, germanium
	indium	iron and germanium
	iron	aluminium, silica, titanium, bismuth, cadmium, gallium, indium, palladium, rubidium, tantalum, thorium, tin, uranium, zirconium, ytterbium
	mercury	uranium
	nickel	arsenic
	niobium	arsenic
	palladium	silica
	phosphorus	copper, dysprosium, erbium, holmium and terbium
	rubidium	iron and germanium
	silica	iron and germanium,
	sulphur	zinc
	tantalum	iron arsenic and germanium
	thorium	iron and germanium
	zirconium	iron, arsenic and germanium
	uranium	iron, arsenic, germanium and mercury
	tin	iron arsenic and germanium